

BISON Users Manual

BISON Release 1.2

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1 Introduction

BISON [1] is a finite element-based nuclear fuel performance code applicable to a variety of fuel forms including light water reactor fuel rods, TRISO particle fuel [2], and metallic rod [3] and plate fuel. It solves the fully-coupled equations of thermomechanics and species diffusion, for 1D spherically symmetric, 2D axisymmetric or 3D geometries. Fuel models are included to describe temperature and burnup dependent thermal properties, fission product swelling, densification, thermal and irradiation creep, fracture, and fission gas production and release. Plasticity, irradiation growth, and thermal and irradiation creep models are implemented for clad materials. Models are also available to simulate gap heat transfer, mechanical contact, and the evolution of the gap/plenum pressure with plenum volume, gas temperature, and fission gas addition. BISON is based on the MOOSE framework [4] and can therefore efficiently solve problems using standard workstations or very large high-performance computers.

Two input files are required as input when running BISON. One is a mesh file. While MOOSE supports several file formats, the ExodusII [5] format is the one used almost exclusively in BISON. This file commonly has “e” as its file extension. The mesh file may be generated using CUBIT [6] or another meshing tool. A further option is a meshing script bundled with BISON. This script, dependent on CUBIT and suitable for LWR fuel rod meshes, is the subject of Chapter 26.

The second file is a text file. This file commonly has “i” as its extension and contains a description of the variables, equations, boundary conditions, and material models associated with an analysis. The structure of the text input file is the main focus of this document.

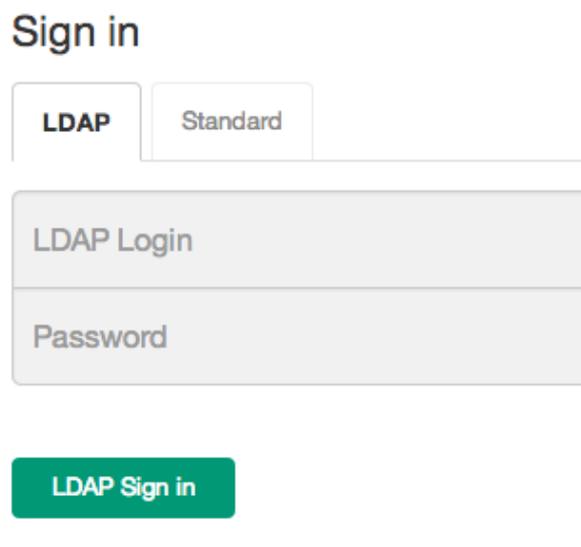
2 Running BISON

2.1 Checking Out the Code

BISON is now hosted on GitLab and the process of checking out the code has significantly changed since SVN. The instructions for checking out the code is different depending upon whether you are an internal (INL onsite user) or external user. These instructions are only for checking out and running the code. If you plan to contribute to BISON detailed instructions for contributing can be found on the [idaholab/bison](#) wiki page on GitLab.

2.1.1 Internal Users

The first step is to obtain an INL High Performance Computing (HPC) account. Once HPC access has been granted go to the GitLab website (<https://hpcgitlab.inl.gov/>) and login with your HPC username and password on the LDAP tab shown in Figure 2.1.



The image shows a 'Sign in' form on a web page. At the top, there are two tabs: 'LDAP' (which is selected) and 'Standard'. Below the tabs is a large grey rectangular box containing two input fields: 'LDAP Login' and 'Password'. Below this box is a green button with the text 'LDAP Sign in' in white. The entire form is centered on the page.

Figure 2.1: GitLab login screen.

Once logged in and access has been granted to the [idaholab/bison](#) repository the following steps are required for the initial checkout of the code:

First add an SSH key to your GitLab profile. To do so execute the code below in a terminal. and copy-paste the key to the 'My SSH Keys' section under the 'SSH' tab in your user profile on GitLab.

```
ssh-keygen -t rsa -C "your_email"  
cat ~/.ssh/id_rsa.pub
```

Then copy-paste the key to the 'My SSH Keys' section under the 'SSH' tab in your user profile on GitLab. Next clone the BISON GitLab repository.

```
cd ~/projects/  
git clone git@hpcgitlab.inl.gov:idaholab/bison.git
```

Next initialize the MOOSE submodule:

```
cd ~/projects/bison/  
git submodule update --init
```

It is necessary to build libMesh before building any application:

```
cd ~/projects/bison/moose/scripts  
./update_and_rebuild_libmesh.sh
```

Once libMesh has compiled successfully, you may now compile BISON:

```
cd ~/projects/bison/  
make (add -jn to run on multiple "n" processors)
```

Once BISON has compiled successfully, it is recommended to run the tests to make sure the version of the code you have is running correctly.

```
cd ~/projects/bison/  
./run_test (add -jn to run "n" jobs at one time)
```

2.1.2 External Users

For external users there are a few additional steps to checking out the code. First request an HPC account. This can be requested at the HPC registration page (<https://secure.inl.gov/caims/>). Once an HPC account has been generated an ssh tunnel will need to be set up to access GitLab. Add the following lines to your `/.ssh/config` file. Replace `<USERNAME>` with the username for your HPC account.

```
#Multiplex connections for less RSA typing  
Host *  
    ControlMaster auto  
    ControlPath ~/.ssh/master-%r@%h:%p  
  
# General Purpose HPC Machines  
Host eos hpcsc flogin1 flogin2 quark  
    User <USERNAME>  
    ProxyCommand ssh <USERNAME>@hpclogin.inl.gov netcat %h %p  
  
#GitLab  
Host hpcgitlab.inl.gov
```

```
User <USERNAME>
ProxyCommand nc -x localhost:5555 %h %p

#Forward license servers, webpages, and source control
Host hpclogin hpclogin.inl.gov
    User <USERNAME>
    HostName hpclogin.inl.gov
    LocalForward 8080 hpcweb:80
    LocalForward 4443 hpcsc:443
```

Next create a tunnel into the HPC environment and leave it tunneling while you require access to GitLab. If you close this window, you close the connection:

```
ssh -D 5555 username@hpclogin.inl.gov
```

Then you have to adjust your socks proxy settings for your web browser to reflect the following settings localhost:5555

If you do not know how to do that, look up **Change socks proxy settings for <insert the name of your web browser here>** on google.com or some other search engine. Once that is complete you can login to the GitLab website. The rest of the steps for checking out the code are the same as for internal users.

2.2 Updating BISON

If it has been some time since you have checked out the code an update will be required to gain access to the new features within BISON. The following instructions apply to both internal and external users to update the code. Note that external users must have their ssh tunnel set up prior to proceeding. First update BISON:

```
cd ~/projects/bison/
git pull
```

Then update the MOOSE submodule:

```
cd ~/projects/bison/
git submodule update
```

Next rebuild libMesh:

```
cd ~/projects/bison/moose/scripts/
./update_and_rebuild_libmesh.sh
```

And finally recompile BISON:

```
cd ~/projects/bison/
make (add -jn to run on multiple "n" processors)
```

2.3 Executing BISON

When first starting out with BISON, it is recommended to start from an example problem similar to the problem that you are trying to solve. Multiple examples can be found at `bison/examples/` and `bison/assessment/`. It may be worth running the example problems to see how the code works and modifying input parameters to see how the run time, results and convergence behavior change.

To demonstrate running BISON, consider the `inputSmearred.i` example problem.

```
cd ~/projects/bison/examples/2D-RZ_rodlet_10pellets
# To run with one processor
~/projects/bison/bison-opt -i inputSmearred.i
# To run in parallel (4 processors)
mpirun -n 4 ../../bison-opt -i inputSmearred.i
```

2.4 Getting Started

2.4.1 Input to BISON

Before running any problem, the power function, axial profile, mesh, and any functions needed for boundary conditions need to be generated.

Typically, a `PiecewiseLinear` function is used together with an external data file to specify a complex power history. This file has time and power specified in columns or rows, with the first row (or column) being the time (seconds) and the second row (or column) being power (W/m). Any data file that is used as input to BISON must be in Windows comma separated values (csv) format. Looking at `inputSmearred.i`, the power history is specified as:

```
[./power_history]
type = PiecewiseLinear
data_file = powerhistory.csv
format = rows
scale_factor = 1.0
[../]
```

The axial power profile, if present, is input as a `PiecewiseBilinearFile`. The axial peaking factors are input as a table within the file, with the top row being the axial location from the bottom of the rod and the left column as time. The axial peaking factors used for the example problem `inputSmearred.i` for the first three axial locations is as follows:

```
          9.44E-03, 1.54E-02, 2.13E-02
0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00
1.00E+00, 5.37E-01, 8.68E-01, 1.01E+00
1.50E+08, 5.37E-01, 8.68E-01, 1.01E+00
```

The mesh can either be generated with the mesh script described in Chapter 26, or if you do not have CUBIT, you can generate a simple 2D-RZ axisymmetric mesh with smeared solid fuel pellets (single fuel column) with the `SmearredPelletMesh` within BISON. To generate the mesh similar to the one used in the example problem `inputSmearred.i`, the mesh block would look like:

```

[Mesh]
  type = SmearedPelletMesh
  clad_mesh_density = customize
  pellet_mesh_density = customize
  ny_p = 80 # Total number of axial elements in fuel
  nx_p = 11 # Number of radial elements in fuel
  nx_c = 5 # Number of elements through thickness of clad
  ny_cu = 3 # Number of axial element of upper clad gap
  ny_c = 80 # Number of axial elements of clad wall
  ny_cl = 3 # Number of axial elements of lower clad cap
  clad_thickness = 5.6e-4
  pellet_outer_radius = 0.0041
  clad_bot_gap_height = 1.0e-3
  pellet_quantity = 10
  pellet_height = 0.01186
  plenum_fuel_ratio = 0.045 # or use clad_top_gap_height = 3.0e-3
  clad_gap_width = 8e-5
  top_bot_clad_height = 2.24e-3
  elem_type = QUAD8
  displacements = 'disp_x disp_y'
  patch_size = 1000
[]

```

2.4.2 Post Processing

BISON typically writes solution data to an ExodusII file. Data may also be written in other formats, a simple comma separated file giving global data being the most common.

Several options exist for viewing ExodusII results files. These include commercial as well as open-source tools. One good choice is Paraview, which is open-source.

Paraview is available on a variety of platforms. It is capable of displaying node and element data in several ways. It will also produce line plots of global data or data from a particular node or element. A complete description of Paraview is not possible here, but a quick overview of using Paraview with BISON results is available in the BISON workshop material.

2.4.3 Graphical User Interface

It is worth noting that a graphical user interface (GUI) exists for all MOOSE-based applications. This GUI is named Peacock. Information about Peacock and how to set it up for use may be found on the MOOSE wiki page.

Peacock may be used to generate a text input file. It is also capable of submitting the analysis. Finally, it provides basic post processing capabilities.

3 Overview

3.1 Basic Syntax

The input file used by BISON is broken into sections or blocks identified with square brackets. The type of input block is placed in the opening brackets, and empty brackets mark the end of the block.

```
[BlockName]
  <block lines and subblocks>
[]
```

Each block may have subblocks, which may in turn have subblocks. The `Functions` block, for example, will have multiple subblocks, each corresponding to a specific function. The line commands in the `Functions` subblocks will describe the function details.

subblocks are opened and closed as

```
[./subblock_name]
  <line commands>
[../]
```

Note that the name given in the subblocks must be unique when compared with all other subblocks in the current block.

Line commands are given as key/value pairs with an equal sign between them. They specify parameters to be used by the object being described. The key is a string (no whitespace), and the value may be a string, an integer, a real number, or a list of strings, integers, or real numbers. Lists are given in single quotes and are separated by whitespace.

Often subblocks will include a `type` line command. This line command specifies the particular type of object being described. The object type indicates which line commands are appropriate for describing the object. BISON will give an error message if a line command is given that does not apply for the current object type. An error message will also be given if a line command is repeated within the current block or if a line command is unused during the initial setup of the simulation.

In this document, line commands are shown with the keyword, an equal sign, and, in angle brackets, the value. If a default value exists for that line command, it is shown in parentheses.

In the initial description of a block, line commands common to all subblocks will be described. Those line commands are then omitted from the description of the subblocks but are nonetheless valid line commands for those subblocks.

The name of a subblock (`[./<name>]`) is most often arbitrary. However, the names of subblocks of `Variables`, `AuxVariables`, and `Postprocessors` define the names used for those entities.

3.2 BISON Syntax Page

A complete listing of all input syntax options in MOOSE is available on the MOOSE Documentation page. See the section on Input File Documentation. Note also that you can run `./bison-opt --dump` to get a list of valid input options for BISON.

3.3 Units

Because BISON uses several empirical models, BISON input expects SI units. This simplifies model input by eliminating the possibility of one set of units for one model and another set of units for a different model. Any needed unit conversions are done inside BISON.

3.4 High-Level Description of a BISON Simulation

The primary purpose of BISON is to solve coupled systems of partial differential equations (PDEs), where the equations represent important physics related to engineering scale nuclear fuel behavior. Fuel simulations typically consist of solving the following energy, momentum, and mass (or species) conservation equations,

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} - e_f \dot{F} = 0, \quad (3.1)$$

$$\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{f} = 0. \quad (3.2)$$

$$\frac{\partial C}{\partial t} + \nabla \cdot \mathbf{J} + \lambda C - S = 0, \quad (3.3)$$

In Equation 3.1, T , ρ and C_p are the temperature, density and specific heat, respectively, e_f is the energy released in a single fission event, and \dot{F} is the volumetric fission rate.

Momentum conservation (Equation 3.2) is prescribed assuming static equilibrium at each time increment where $\boldsymbol{\sigma}$ is the Cauchy stress tensor and \mathbf{f} is the body force per unit mass (e.g. gravity). The displacement field u , which is the primary solution variable, is connected to the stress field via the strain, through a constitutive relation.

In the equation for species conservation (3.3) C , λ , and S are the concentration, radioactive decay constant, and source rate of a given species, respectively.

Often, fuels performance problems are limited to thermomechanics, where only Equations 3.1 and 3.2 are solved.

Each term in Equations 3.1 - 3.3 (time derivatives, divergence, source, sinks, etc.) are referred to as kernels and are discussed in greater detail in Chapter 14.

These equations are solved simultaneously using the finite element method (FEM) and JFNK approach [7] on a discretized domain. The domain (also referred to as a mesh) may represent uranium dioxide fuel pellets and zirconium clad in a light water reactor (LWR) simulation. Blocks, side sets, and node sets are defined on the mesh such that material models and boundary

conditions can be assigned to different parts of the model. Details regarding the mesh, material models, and boundary conditions can be found in chapters 6, 16, and 10 respectively.

Kernels, boundary conditions, and material models may require supporting information and calculations. This is achieved through the use of Functions and AuxKernels, which are detailed in chapters 9 and 12. For example, a function can be used to define power and time value pairs, which would inform the source term in the energy equation (Equation 3.1). An AuxKernel could be used to define fission rate or burnup, which could be used to inform material models that are dependent on those values. AuxKernels can also be used for writing information, such as stress components, to the output file.

Execution on the analysis is described in the Executioner block. Line commands describe time stepping details and solver options. See Chapter 19 for details.

MOOSE Postprocessors compute a single scalar value at each timestep. These can be minimums, maximums, averages, volumes, or any other scalar quantity. One example of the use of Postprocessors in BISON is computing the gas volume of an LWR rod. The gas volume changes timestep to timestep, but since it is a single scalar quantity, a Postprocessor computes this value. Chapter 18 gives examples.

The following sections delve deeper into the topics mentioned here. The format basically follows that of a typical BISON LWR input file and provides details for each section. Required parameters have **Required** included in their description throughout the document.

4 Global Parameters

The `GlobalParams` block specifies parameters that are available, as appropriate, in any other block or subblock in the input file. For example, imagine a subblock that accepts a line command with the keyword `value`. If the subblock has a line command for `value`, that line command will be used regardless of what is in `GlobalParams`. However, if the line command is missing in the subblock but defined in `GlobalParams`, the subblock will use the parameter defined in `GlobalParams`. In the example below, the line commands `order = FIRST` and `family = LAGRANGE` will be available in all blocks and subblocks in the remainder of the input file.

```
[GlobalParams]
  order = FIRST
  family = LAGRANGE
[]
```

5 Problem

The `Problem` block is typically only used to indicate that a model should run as axisymmetric (`RZ`) or spherically symmetric (`RSPHERICAL`). If the model is 3D, the `Problem` block may be omitted.

```
[Problem]
  coord_type = <string>
[]
```

There are two advanced cases that require a `[Problem]` block to be included in the input file. These cases are known as `ReferenceResidualProblem` and `FrictionalContactProblem`. When using either of these types there are many required additions throughout the input file. Therefore `ReferenceResidualProblem` and `FrictionalContactProblem` are discussed in Chapters 24 and 25 respectively.

6 Mesh

The `Mesh` block's purpose is to give details about the finite element mesh to be used. Typically meshes for BISON simulations are created using the mesh generation tool Cubit (known as Trelis for non-DOE users). For simulations of LWR fuel there is a mesh script found in `bison/tools/UO2/`. The details of the mesh script are provided in Chapter 26.

```
[Mesh]
  file = <string>
  displacements = <string list>
  patch_size = <integer> (40)
[]
```

<code>file</code>	Required. This is the mesh file name. BISON uses ExodusII mesh files.
<code>displacements</code>	List of the displacement variables. This line must be given if the analysis is to use contact or nonlinear geometry. Typically <code>'disp_x disp_y'</code> for an axisymmetric analysis.
<code>patch_size</code>	Number of nearby elements to consider as possible contacting surfaces. The value for the patch size depends upon whether Dirac or Constraint based contact is used. For Dirac a typical value is 1000. For Constraint it is ideal to choose a small enough patch size that encompasses all possible contacting surfaces to reduce memory requirements. For example, if the fuel moves up the clad 8 nodes make the patch size 20. This will allow the contact search to use 10 nodes above and 10 nodes belows the point at which the fuel comes into contact with the clad.

For users that do not have access to Cubit or Trelis but want to simulate LWR fuel there is a `SmearedPelletMesh` type that can be used to generate a mesh for modeling a smeared column of fuel (i.e. no dishes and or chamfers). The structure of the `SmearedPelletMesh` block is outlined below:

```
[Mesh]
  type = SmearedPelletMesh
  clad_mesh_density = <string> (medium)
  pellet_mesh_density = <string> (medium)
  ny_p = <integer> (24)
  nx_p = <integer> (8)
  nx_c = <integer> (2)
  ny_cu = <integer> (1)
  ny_c = <integer> (24)
  ny_cl = <integer> (1)
```

```

clad_thickness = <real> (0.00041)
pellet_outer_radius = <real> (0.0041)
clad_bot_gap_height = <real> (0.00127)
pellet_quantity = <real> (2)
elem_type = <string> (QUAD4)
displacements = <string list>
patch_size = <integer> (4)
[]

```

type	SmearedPelletMesh
clad_mesh_density	Mesh density of the clad. Choices are coarse, medium, fine or custom. Default is medium.
pellet_mesh_density	Mesh density of the fuel pellets. Choices are coarse, medium, fine or custom. Default is medium.
ny_p	Number of finite elements in a fuel pellet in the axial direction.
nx_p	Number of finite elements in a fuel pellet in the radial direction.
nx_c	Number of finite elements through the thickness of the cladding in the radial direction.
ny_cu	Number of finite elements through the thickness of the cladding in the axial direction of the upper plug.
ny_c	Number of finite elements axially through the cladding.
ny_cl	Number of finite elements through the thickness of the cladding in the axial direction of the lower plug.
clad_thickness	The cladding thickness.
pellet_outer_radius	The outer radius of the pellet.
clad_bot_gap_height	Gap between bottom of pellet stack and the inside bottom surface of the cladding.
pellet_quantity	Number of pellets to be included.
pellet_height	The height of the pellet.
plenum_fuel_ratio	Ratio of the axial gas height to the fuel height inside the cladding. Either <code>plenum_fuel_ratio</code> or <code>clad_top_gap_height</code> must be specified but not both.
clad_top_gap_height	Gap between top of pellet and inside top surface of cladding. Either <code>plenum_fuel_ratio</code> or <code>clad_top_gap_height</code> must be specified but not both.
clad_gap_width	Gap between outer radius of pellet and inside surface of cladding.
top_bot_clad_height	Thickness of top and bottom cladding walls.
elem_type	Type of finite element. Default is QUAD4. For second-order meshes use QUAD8.

displacements	List of the displacement variables. This line must be given if the analysis is to use contact or nonlinear geometry. Typically 'disp_x disp_y' for an axisymmetric analysis.
patch_size	Number of nearby elements to consider as possible contacting surfaces. The value for the patch size depends upon whether Dirac or Constraint based contact is used. For Dirac a typical value is 1000. For Constraint it is ideal to choose a small enough patch size that encompasses all possible contacting surfaces to reduce memory requirements. For example, if the fuel moves up the clad 8 nodes make the patch size 20. This will allow the contact search to use 10 nodes above and 10 nodes below the point at which the fuel comes into contact with the clad.

7 Variables

The `Variables` block is where all of the primary solution variables are identified. The name of each variable is taken as the name of the subblocks. Primary solution variables often include temperature (usually named `temp`) and displacement (usually named `disp_x`, `disp_y`, and `disp_z`).

```
[Variables]
  [./var1]
    order = <string>
    family = <string>
  [../]
  [./var2]
    order = <string>
    family = <string>
    initial_condition = <real>
    scaling = <real> (1)
  [../]
[]
```

<code>order</code>	The order of the variable. Typical values are <code>FIRST</code> and <code>SECOND</code> .
<code>family</code>	The finite element shape function family. A typical value is <code>LAGRANGE</code> .
<code>initial_condition</code>	Optional initial value to be assigned to the variable. Zero is assigned if this line is not present.
<code>scaling</code>	Amount to scale the variable during the solution process. This scaling affects only the residual and preconditioning steps and not the final solution values. This line command is sometimes helpful when solving coupled systems where one variable's residual is orders of magnitude different than the other variables' residuals.

8 AuxVariables

The `AuxVariables` block is where all of the auxiliary variables are identified. The name of each variable is taken as the name of the subblocks. Auxiliary variables are used for quantities such as fast neutron flux, element-averaged stresses, and other output variables.

```
[AuxVariables]
  [./var1]
    order = <string>
    family = <string>
  [../]
  [./var2]
    order = <string>
    family = <string>
    initial_condition = <real>
  [../]
[]
```

<code>order</code>	The order of the variable. Typical values are <code>CONSTANT</code> , <code>FIRST</code> , and <code>SECOND</code> .
<code>family</code>	The finite element shape function family. Typical values are <code>MONOMIAL</code> and <code>LAGRANGE</code> .
<code>initial_condition</code>	Optional initial value to be assigned to the variable. Zero is assigned if this line is not present.

9 Functions

9.1 Composite

The `Composite` function takes an arbitrary set of functions, provided in the `functions` parameter, evaluates each of them at the appropriate time and position, and multiplies them together. The function can optionally be multiplied by a scale factor, which is specified using the `scale_factor` parameter.

```
[./composite]
  type = CompositeFunction
  functions = <string list>
  scale_factor = <real> (1.0)
[../]
```

`type` `CompositeFunction`
`functions` **List of functions to be multiplied together.**
`scale_factor` **Scale factor to be applied to resulting function. Default is 1.**

9.2 ParsedFunction

The `ParsedFunction` function takes a mathematical expression in `value`. The expression can be a function of time (`t`) or coordinate (`x`, `y`, or `z`). The expression can include common mathematical functions. Examples include `'4e4+1e2*t'`, `'sqrt(x*x+y*y+z*z)'`, and `'if(t<=1.0, 0.1*t, (1.0+0.1)*cos(pi/2*(t-1.0)) - 1.0)'`. Constant variables may be used in the expression if they have been declared with `vars` and defined with `vals`. Further information can be found at <http://warp.povusers.org/FunctionParser/>.

```
[./parsedfunction]
  type = ParsedFunction
  value = <string>
  vals = <real list>
  vars = <string list>
[../]
```

`type` `ParsedFunction`
`value` **Required.** String describing the function.
`vals` **Values to be associated with variables in vars.**
`vars` **Variable names to be associated with values in vals.**

9.3 PiecewiseBilinear

The `PiecewiseBilinear` function reads a csv file and interpolates values based on the data in the file. The interpolation is based on x-y pairs. If `axis` is given, time is used as the y index. Either `xaxis` or `yaxis` or both may be given. Time is used as the other index if one of them is not given. If `radius` is given, `xaxis` and `yaxis` are used to orient a cylindrical coordinate system, and the x-y pair used in the query will be the radial coordinate and time.

```
[./piecewiselinear]
type = PiecewiseBilinear
data_file = <string>
axis = <0, 1, or 2 for x, y, or z>
xaxis = <0, 1, or 2 for x, y, or z>
yaxis = <0, 1, or 2 for x, y, or z>
scale_factor = <real> (1.0)
radial = <bool> (false)
[../]
```

<code>type</code>	<code>PiecewiseBilinear</code>
<code>data_file</code>	File holding your csv data.
<code>axis</code>	Coordinate direction to use in the function evaluation.
<code>xaxis</code>	Coordinate direction used for x-axis data.
<code>yaxis</code>	Coordinate direction used for y-axis data.
<code>scale_factor</code>	Scale factor to be applied to resulting function. Default is 1.
<code>radial</code>	Set to <code>true</code> if interpolation should be done along a radius rather than along a specific axis. Requires <code>xaxis</code> and <code>yaxis</code> .

9.4 PiecewiseConstant

The `PiecewiseConstant` function defines the data using a set of x-y data pairs. Instead of linearly interpolating between the values, however, the `PiecewiseConstant` function is constant when the abscissa is between the values provided by the user. The `direction` parameter controls whether the function takes the value of the abscissa of the user-provided point to the right or left of the value at which the function is evaluated.

```
[./piecewiseconstant]
type = PiecewiseConstant
x = <real list>
y = <real list>
xy_data = <real list>
data_file = <string>
format = <string> (rows)
scale_factor = <real> (1.0)
axis = <0, 1, or 2 for x, y, or z>
directon = <string> (left)
```

```
[../]
```

<code>type</code>	<code>PiecewiseConstant</code>
<code>x</code>	List of x values for x-y data.
<code>y</code>	List of y values for x-y data.
<code>xy_data</code>	List of pairs of x-y data points.
<code>data_file</code>	Name of an file containing x-y data.
<code>format</code>	Format of x-y data in external file.
<code>scale_factor</code>	Scale factor to be applied to resulting function. Default is 1.
<code>axis</code>	Coordinate direction to use in the function evaluation. If not present, time is used as the function input.

9.5 PiecewiseLinear

The `PiecewiseLinear` function performs linear interpolations between user-provided pairs of x-y data. The x-y data can be provided in three ways. The first way is through a combination of the `x` and `y` parameters, which are lists of the x and y coordinates of the data points that make up the function. The second way is in the `xy_data` parameter, which is a list of pairs of x-y data that make up the points of the function. This allows for the function data to be specified in columns by inserting line breaks after each x-y data point. Finally, the x-y data can be provided in an external file containing comma-separated values. The file name is provided in `data_file`, and the data can be provided in either rows (default) or columns, as specified in the `format` parameter.

By default, the x-data corresponds to time, but this can be changed to correspond to x, y, or z coordinate with the `axis` line. If the function is queried outside of its range of x data, it returns the y value associated with the closest x data point.

```
[./piecewiselinear]
type = PiecewiseLinear
x = <real list>
y = <real list>
xy_data = <real list>
data_file = <string> (rows)
format = <string>
scale_factor = <real> (1.0)
axis = <0, 1, or 2 for x, y, or z>
[../]
```

<code>type</code>	<code>PiecewiseLinear</code>
<code>x</code>	List of x values for x-y data.
<code>y</code>	List of y values for x-y data.
<code>xy_data</code>	List of pairs of x-y data points.

<code>data_file</code>	Name of an file containing x-y data.
<code>format</code>	Format of x-y data in external file.
<code>scale_factor</code>	Scale factor to be applied to resulting function. Default is 1.
<code>axis</code>	Coordinate direction to use in the function evaluation. If not present, time is used as the function input.

10 Boundary Conditions

The BCs block is for specifying various types of boundary conditions.

```
[BCs]
  [./name]
    type = <BC type>
    boundary = <string list>
    ...
  [../]
[]
```

type Type of boundary condition.

boundary List of boundaries (side sets). Either boundary numbers or names.

10.1 BulkCoolantBC

The BulkCoolantBC boundary condition determines the heat transfer from a boundary based upon a bulk coolant temperature and coolant heat transfer coefficient.

```
[./bulkcoolantBC]
  type = BulkCoolantBC
  variable = <variable>
  boundary = <string list>
  bulk_temperature = <real> (800)
  heat_transfer_coefficient = <real> (2000)
[../]
```

type BulkCoolantBC

variable **Required.** Primary variable associated with this boundary condition.

boundary **Required.** List of boundary names or ids where this boundary condition will apply.

bulk_temperature The bulk coolant temperature.

heat_transfer_coefficient The heat transfer coefficient of the coolant.

10.2 ConvectiveFluxBC

The ConvectiveFluxBC boundary condition determines the value on a boundary based upon the initial and final values, the flux through the boundary and the duration of exposure..

```
[./convectivefluxBC]
  type = ConvectiveFluxBC
  variable = <variable>
  boundary = <string list>
  initial = <real> (500)
  final = <real> (500)
  rate = <real> (7500)
[../]
```

type	ConvectiveFluxBC
variable	Required. Primary variable associated with this boundary condition.
boundary	Required. List of boundary names or ids where this boundary condition will apply.
initial	The initial value of the variable on the boundary.
final	The final value of the variable on the boundary.
rate	The flux of the variable through the boundary.

10.3 ConvectiveFluxFunction

The ConvectiveFluxFunction boundary condition determines the value on a boundary based upon the heat transfer coefficient of the fluid on the outside of boundary and far-field temperature.

```
[./convectivefluxFunction]
  type = ConvectiveFluxFunction
  variable = <variable>
  boundary = <string list>
  T_infinity= <string>
  coefficient = <real>
  coefficient_function = <string>
[../]
```

type	ConvectiveFluxFunction
variable	Required. Primary variable associated with this boundary condition.
boundary	Required. List of boundary names or ids where this boundary condition will apply.
T_infinity	Required. The name of the function describing the far-field temperature.

`coefficient` **Required.** The heat transfer coefficient of the fluid in contact with the boundary. If `coefficient_function` is provided this coefficient multiplies the function.

`coefficient_function` Function describing the heat transfer coefficient.

10.4 CoolantChannel

The effect of the coolant on the heat transfer at the exterior cladding surface can be modeled using the `CoolantChannel` feature. This feature appears in the input file in its own block (i.e., not inside the BCs block).

The presence of some input parameters causes others to be ignored. The following describes the input parameter precedence.

If `heat_transfer_coefficient` is given, its value will be assigned to the given boundary. All other parameters related to the heat transfer coefficient calculation are ignored.

Enthalpy is taken as `coupledEnthalpy` if present. Otherwise, heat flux is calculated based on `linear_heat_rate`, **specification of `number_axial_zone`**, and **specification of `heat_flux`**, in highest precedence order. The integrated heat flux is computed based on the same precedence. As an example, if `number_axial_zone` and `heat_flux` are specified, `heat_flux` will be ignored. These are used as inputs to the heat transfer coefficient correlations.

The `coolant_material` is water by default. It can be instead set to sodium, and a heat transfer correlation for liquid sodium is used. With sodium coolant, calculations for phase change are disabled. By default, the subchannel geometry is set to triangular if the user selects sodium coolant, but this can be changed to a square channel if desired.

```
[CoolantChannel]
[./coolantchannel]
boundary = <string list>
variable = <string>
axial_power_profile = <string>
blockage_ratio = <real> (0)
chf_correlation_type=<int> (4)
compute_enthalpy =<bool> (true)
cond_metal = <real>
cond_oxide = <real>
coolant_material = <string>
coupledEnthalpy = <string>
direction = <string>
direction2 = <string>
flooding_rate = <real>
flooding_time = <real>
flow_area = <real>
fuel_stack_length = <real>
fuel_stack_bottom = <real>
heat_flux = <string>
heat_transfer_coefficient = <string or real>
heat_transfer_mode = <string> (0)
```

```

heated_diameter = <real>
heated_perimeter = <real>
htc_correlation_type = <string>
hydraulic_diameter = <real>
initial_power = <real>
initial_temperature = <real>
inlet_massflux = <string or real>
inlet_pressure = <string or real>
inlet_temperature = <string or real>
input_Tchf = <real> (0)
input_Tmin = <real> (0)
input_rewetting_htc = <real> (1.0e5)
linear_heat_rate = <string>
model_post_chf = <bool> (true)
number_axial_zone = <integer> (0)
number_lateral_zone = <integer> (1)
oxide_thickness = <string>
oxide_model = <string> (zirconia)
pbr = <real>
reflooding_model = <int> (1)
rod_diameter = <real> (0.01)
rod_pitch = <real> (0.0126)
specified_height = <real> (0)
subchannel_geometry = <string>
[../]
[]

```

boundary	Required. List of boundaries. Typically only one boundary id is given.
variable	Required. Name of variable associated with this BC. Typically temp.
axial_power_profile	Function name for function describing axial power factors.
blockage_ratio	Flow blockage ratio used in FLECHT correlations.
chf_correlation_type	CHF correlatons. one of 1 for EPRI, 2 for GE, 3 for Zuber, and 4 for BIASI.
compute_enthalpy	option to turn on /off the enthalpy calculation.
cond_metal	Conductivity of the metal. Used if oxide_model is user.
cond_oxide	Conductivity of the oxide. Used if oxide_model is user.
coolant_material	Water or sodium. Defaults to water.
coupledEnthalpy	Variable name. If given, enthalpy is taken from this variable directly instead of being calculated.
direction	One of x, y, or z. Coordinate direction associated with fluid flow. Default is y.

<code>direction2</code>	One of x, y, or z. Coordinate direction associated with lateral dimension of model. Default is x. This input is used for plate geometry.
<code>flooding_rate</code>	Inlet flooding rate.
<code>flooding_time</code>	The starting time of flooding.
<code>flow_area</code>	Flow area. If used, must be used with <code>heated_diameter</code> , <code>heated_perimeter</code> , and <code>hydraulic_diameter</code> . If used, <code>rod_diameter</code> and <code>rod_pitch</code> will be ignored.
<code>fuel_stack_bottom</code>	The axial position of the fuel stack bottom.
<code>fuel_stack_length</code>	The length of fuel stacks.
<code>heat_flux</code>	Function name for function describing the heat flux at the cladding surface.
<code>heat_transfer_coefficient</code>	Either a function name for a function describing the heat transfer coefficient or a real value to be assigned as the heat transfer coefficient. If present, other parameters controlling the heat transfer coefficient calculation will be ignored.
<code>heat_transfer_mode</code>	One of 0 (automatic), 1 (natural convection), 2 (forced liquid convection), 3 (subcooled boiling), 4 (saturated boiling), 5 (transition boiling), 6 (film boiling), and 7 (single phase vapor).
<code>heated_diameter</code>	Heated diameter. If used, must be used with <code>flow_area</code> , <code>heated_perimeter</code> , and <code>hydraulic_diameter</code> . If used, <code>rod_diameter</code> and <code>rod_pitch</code> will be ignored.
<code>heated_perimeter</code>	Heated perimeter. If used, must be used with <code>flow_area</code> , <code>heated_diameter</code> , and <code>hydraulic_diameter</code> . If used, <code>rod_diameter</code> and <code>rod_pitch</code> will be ignored.
<code>htc_correlation_type</code>	One of 1 (Thom), 2 (Jens Lottes), 3(Chen) or 4 (Shrock-Grossman) for pre-CHF correlations; or 1 (McDonough-Milich-King) and 2 (modified Condie-Bengtson) for transition boiling correlations; or 1 (Groenveld) and 2 (Dougall-Rohsenow) for film boiling correlations.
<code>hydraulic_diameter</code>	Hydraulic diameter. If used, must be used with <code>flow_area</code> , <code>heated_perimeter</code> , and <code>heated_diameter</code> . If used, <code>rod_diameter</code> and <code>rod_pitch</code> will be ignored.
<code>initial_power</code>	Initial peak power (kW/m).
<code>initial_temperature</code>	Initial peak clad temperature.
<code>inlet_massflux</code>	Either a function name for a function describing the inlet mass flux or a real value to be assigned as the inlet mass flux.

inlet_pressure	Either a function name for a function describing the inlet pressure or a real value to be assigned as the inlet pressure.
inlet_temperature	Either a function name for a function describing the inlet temperature or a real value to be assigned as the inlet temperature.
input_Tchf	Input temperature at critical heat flux.
input_Tmin	Input rewetting temperature.
input_rewetting_htc	Input rewetting heat transfer coefficient.
linear_heat_rate	Function name for a function describing the linear heat rate.
number_axial_zone	Number of axial divisions along the cladding to be used in integrating the heat flux.
number_lateral_zone	Number of lateral divisions along the cladding to be used in integrating the heat flux. This input is used for plate geometry.
model_post_chf	Option to turn on or off post-CHF calculations.
oxide_thickness	Name of <code>AuxVariable</code> representing the oxide thickness. If not given, the calculated heat transfer coefficient will not account for an oxide layer.
oxide_model	One of zirconia, alumina, or user.
reflooding_model	Model options for modeling reflooding : either 0 <i>oldcorrelation</i> or 1 <i>newWestinghousecorrelation</i> .
rod_diameter	Diameter of the fuel rod.
rod_pitch	Pitch or spacing between fuel rods.
specified_height	The input to compute reflooding heat transfer at a specified axial location; used for testing purpose only.
subchannel_geometry	Geometry of the pin array: either square or triangular. If not specified, the geometry is square if the coolant is water or triangular if the coolant is sodium.

10.5 Dirichlet

10.5.1 DirichletBC

```
[./dirichletbc]
  type = DirichletBC
  variable = <variable>
  boundary = <string list>
  value = <real>
[../]
```

type DirichletBC
 variable **Required.** Primary variable associated with this boundary condition.
 boundary **Required.** List of boundary names or ids where this boundary condition will apply.
 value **Required.** Value to be assigned.

10.5.2 PresetBC

The `PresetBC` takes the same inputs as `DirichletBC` and also acts as a Dirichlet boundary condition. However, the implementation is slightly different. `PresetBC` causes the value of the boundary condition to be applied before the solve begins where `DirichletBC` enforces the boundary condition as the solve progresses. In certain situations, one is better than another.

10.5.3 FunctionDirichletBC

```
[./functiondirichletbc]
  type = FunctionDirichletBC
  variable = <variable>
  boundary = <string list>
  function = <string>
[../]
```

type FunctionDirichletBC
 variable **Required.** Primary variable associated with this boundary condition.
 boundary **Required.** List of boundary names or ids where this boundary condition will apply.
 function **Required.** Function that will give the value to be applied by this boundary condition.

10.5.4 FunctionPresetBC

The `FunctionPresetBC` takes the same inputs as `FunctionDirichletBC` and also acts as a Dirichlet boundary condition. However, the implementation is slightly different. `FunctionPresetBC` causes the value of the boundary condition to be applied before the solve begins where `FunctionDirichletBC` enforces the boundary condition as the solve progresses. In certain situations, one is better than another.

10.6 DryCaskHeatFlux

The `DryCaskHeatFlux BC` is used to model the heat flux from a rod in the center of a fuel assembly, stored inside a dry cask storage system (DCSS). The flux includes radiative and conductive effects inside the assembly and conductive/convective effects from the assembly to ambient.

```
[./decay_heat_in_dcass]
type = DryCaskHeatFlux
variable = <variable>
boundary = <string list>
bwr_or_pwr = <string>
fill_gas = <string>
ambient_temperature = <real>
cask_effective_htc = <real>
start_time = <real>
drying_duration = <real>
[../]
```

type	DryCaskHeatFlux
variable	Required. Primary variable associated with this boundary condition.
boundary	Required. List of boundaries where this BC will apply.
bwr_or_pwr	Required. Whether to use a typical geometry from a BWR or a PWR assembly.
fill_gas	Required. helium, nitrogen, or vacuum.
ambient_temperature	Temperature outside the cask.
cask_effective_htc	Required. Effective heat transfer coefficient from assembly to ambient (W/K).
start_time	The time when this BC will begin.
drying_duration	If drying (vacuum) is desired, it will be applied immediately after the start_time. After drying in vacuum, the calculation switches from vacuum fill gas to fill_gas specified by the user.

10.7 HydrogenPickup

The HydrogenPickup BC is used to model the flux of hydrogen into the clad that is caused by oxide growth. The flux is approximated as a constant fraction of the hydrogen liberated by oxide growth at the interface between the coolant water and the clad.

Note that this BC must be coupled to a variable that gives the thickness of the oxide over time, such as with the OxideAux kernel. For this to work properly, OxideAux must be set to update on updates to the residual; *it will not work if the OxideAux is set to update on time steps.*

```
[./hydrogen_pickup]
type = HydrogenPickup
variable = <variable>
boundary = <string list>
oxide_thickness = <variable>
pickup_fraction = <real> (0.15)
clad_thickness = <real> (660e-6)
```

```
fuel_pin_geometry = <string>
[../]
```

type	HydrogenPickup
variable	Required. Primary variable associated with this boundary condition.
boundary	Required. List of boundary names or ids where this boundary condition will apply.
oxide_thickness	Required. The coupled variable that gives the oxide thickness on the boundary.
pickup_fraction	The fractional amount of hydrogen liberated by the oxide growth that is absorbed into the clad.
clad_thickness	The initial thickness of the clad; only needed if fuel_pin_geometry is not specified.
fuel_pin_geometry	Name of the FuelPinGeometry object (see 23.1).

10.8 PlenumPressure

The `PlenumPressure` block is used to specify internal rod pressure as a function of temperature, cavity volume, and moles of gas.

The `PlenumPressure` boundary condition uses two levels of nesting within the `BCs` block. This allows the pressure to be applied properly in all coordinate directions although it is specified one time only.

The volume and pressure specified in the plenum pressure block along with the initial condition specified in the temperature variable block are used to calculate the initial moles. The initial moles are then used to update the plenum pressure throughout the simulation. It is worth noting to make sure the initial temperature is set to the temperature of the gas when fabricated, usually room temperature (293 K).

The postprocessors coupled to the plenum pressure boundary condition (gas volume and rod interior temperature) need to be executed at each residual such that the plenum pressure is calculated for that specific timestep. If calculated at each timestep, the calculation uses volume and temperature from the previous step to calculate the plenum pressure for the current step, causing a lag in the plenum pressure used and reported for that timestep.

```
[./PlenumPressure]
[./plenumpressure]
  boundary = <string list>
  initial_pressure = <real> (0)
  initial_temperature = <real>
  startup_time = <real> (0)
  R = <real>
  output_initial_moles = <string>
  temperature = <string>
  volume = <string>
```

```

material_input = <string list>
output = <string>
refab_time = <real list>
refab_pressure = <real list>
refab_volume = <real list>
refab_type = <integer list>
[../]
[../]

```

boundary	Required. List of boundary names or ids where this boundary condition will apply.
initial_pressure	The initial pressure in the plenum.
initial_temperature	The initial temperature of the plenum. If not given, will use the initial value from the <code>Postprocessor</code> given by <code>temperature</code> .
startup_time	The amount of time during which the pressure will ramp from zero to its true value.
R	Required. The universal gas constant. In BISON, SI units are used, and R should be 8.3143.
output_initial_moles	If given, the name to use to report the initial moles of gas.
temperature	Required. The name of the <code>Postprocessor</code> holding the average temperature value.
volume	Required. The name of the <code>Postprocessor</code> holding the internal volume.
material_input	The name of the <code>Postprocessors</code> that hold the amount of material injected into the plenum.
output	If given, the name to use for reporting the plenum pressure value. If not given, the block name will be used.
refab_time	The time(s) at which the plenum pressure must be reinitialized (likely due to fuel rod refabrication).
refab_pressure	The pressure of fill gas at refabrication. Number of values must match number in <code>refab_time</code> .
refab_temperature	The temperature at refabrication. Number of values must match number in <code>refab_time</code> .
refab_volume	The gas volume at refabrication. Number of values must match number in <code>refab_time</code> .

10.9 Pressure

The `Pressure` boundary condition uses two levels of nesting within the `BCs` block. This allows the pressure to be applied properly in all coordinate directions although it is specified one time only.

```
[./Pressure]
  [./pressure]
    boundary = <string list>
    factor = <real> (1)
    function = <string>
  [../]
[../]
```

- boundary **Required.** List of boundary names or ids where this boundary condition will apply.
- factor **Magnitude of pressure to be applied.** If `function` is also given, `factor` is multiplied by the output of the function and then applied as the pressure.
- function **Function that will give the value to be applied by this boundary condition.**

11 Contact

Finite element contact enforces constraints between surfaces in the mesh. Mechanical contact prevents penetration and develops contact forces. Thermal contact transfers heat between the surfaces. In BISON there are currently two systems to choose from for mechanical contact: Dirac and Constraint. Constraint based contact is recommended for two-dimensional problems and Dirac for three-dimensional problems. Constraint contact is more robust but due to the patch size requirement specified in the `Mesh` block constraint contact uses too much memory on 3D problems. Depending upon the contact formalism chosen the solver options to be used change. The details of the solver parameters recommended for Dirac and Constraint contact formalisms are provided in Section 19.2.

11.1 Mechanical Contact

```
[Contact]
  [./contact]
    disp_x = <variable>
    disp_y = <variable>
    disp_z = <variable>
    formulation = <string> (DEFAULT)
    friction_coefficient = <real> (0)
    master = <string>
    model = <string> (frictionless)
    normal_smoothing_distance = <real>
    normal_smoothing_method = <string> (edge_based)
    order = <string> (FIRST)
    penalty = <real> (1e8)
    normalize_penalty = <bool> (false)
    slave = <string>
    system = <string> (Dirac)
    tangential_tolerance = <real>
    tension_release = <real> (0)
  [../]
[]
```

- `disp_x` **Required.** Variable name for displacement variable in x direction. Typically `disp_x`.
- `disp_y` Variable name for displacement variable in y direction. Typically `disp_y`.

<code>disp_z</code>	Variable name for displacement variable in z direction. Typically <code>disp_z</code> .
<code>formulation</code>	One of DEFAULT, KINEMATIC, or PENALTY. DEFAULT is KINEMATIC.
<code>friction_coefficient</code>	The friction coefficient.
<code>master</code>	Required. The boundary id for the master surface.
<code>model</code>	One of frictionless, glued, or coulomb.
<code>normal_smoothing_distance</code>	Distance from face edge in parametric coordinates over which to smooth the contact normal. 0.1 is a reasonable value.
<code>normal_smoothing_method</code>	One of <code>edge_based</code> or <code>nodal_normal_based</code> . If <code>nodal_normal_based</code> , must also have a <code>NodalNormals</code> block.
<code>order</code>	The order of the variable. Typical values are FIRST and SECOND.
<code>penalty</code>	The penalty stiffness value to be used in the constraint.
<code>normalize_penalty</code>	Whether to normalize the penalty stiffness by the nodal area of the slave node.
<code>slave</code>	Required. The boundary id for the slave surface.
<code>system</code>	The system to use for constraint enforcement. Options are Dirac (DiracKernel) or Constraint. The default system is Dirac.
<code>tangential_tolerance</code>	Tangential distance to extend edges of contact surfaces.
<code>tension_release</code>	Tension release threshold. A node will not be released if its tensile load is below this value. If negative, no tension release will occur.

In LWR fuel analysis, the cladding surface is typically the master surface, and the fuel surface is the slave surface. It is good practice to make the master surface the coarser of the two.

The robustness and accuracy of the mechanical contact algorithm is strongly dependent on the penalty parameter. If the parameter is too small, inaccurate solutions are more likely. If the parameter is too large, the solver may struggle.

The DEFAULT option uses an enforcement algorithm that moves the internal forces at a slave node to the master face. The distance between the slave node and the master face is penalized. The PENALTY algorithm is the traditional penalty enforcement technique.

11.2 Thermal Contact

11.2.1 GapHeatTransfer

```
[ThermalContact]
[./thermalcontact]
```

```

type = GapHeatTransfer
disp_x = <variable>
disp_y = <variable>
disp_z = <variable>
emissivity_1 = <real> (0)
emissivity_2 = <real> (0)
gap_conductivity = <real> (1)
gap_conductivity_function = <string>
gap_conductivity_function_variable = <string>
master = <string>
min_gap = <real> (1e-6)
max_gap = <real> (1e6)
normal_smoothing_distance = <real>
normal_smoothing_method = <string> (edge_based)
order = <string> (FIRST)
quadrature = <bool> (false)
slave = <string>
stefan_boltzmann = <real> (5.669e-8)
tangential_tolerance = <real>
variable = <string>
[../]
[]

```

type	GapHeatTransfer
disp_x	Variable name for displacement variable in x direction. Typically disp_x. Optional.
disp_y	Variable name for displacement variable in y direction. Typically disp_y. Optional.
disp_z	Variable name for displacement variable in z direction. Typically disp_z. Optional.
emissivity_1	The emissivity of the fuel surface.
emissivity_2	The emissivity of the cladding surface.
gap_conductivity	The thermal conductivity of the gap material.
gap_conductivity_function	Thermal conductivity of the gap material as a function. Multiplied by gap_conductivity.
gap_conductivity_function_variable	Variable to be used in thermal_conductivity_function in place of time.
master	Required. The boundary id for the master surface.
min_gap	The minimum permissible gap size.
max_gap	The maximum permissible gap size.

normal_smoothing_distance	Distance from face edge in parametric coordinates over which to smooth the contact normal. 0.1 is a reasonable value.
normal_smoothing_method	One of <code>edge_based</code> or <code>nodal_normal_based</code> . If <code>nodal_normal_based</code> , must also have a <code>NodalNormals</code> block.
order	The order of the variable. Typical values are <code>FIRST</code> and <code>SECOND</code> .
quadrature	Whether or not to use quadrature point-based gap heat transfer.
slave	Required. The boundary id for the slave surface.
stefan_boltzmann	The Stefan-Boltzmann constant.
tangential_tolerance	Tangential distance to extend edges of contact surfaces.
variable	Required. The temperature variable name.

The `quadrature` option is recommended with second-order meshes. Also note that the type of conductance used depends on the value of the `coord_type` parameter (`XYZ` (default), `RZ`, or `RSPHERICAL`), which is defined in the `Problem` block.

11.2.2 GapHeatTransferLWR

`GapHeatTransferLWR` differs from `GapHeatTransfer` in that the gap conductivity is computed based on the gases in the gap. To this may also be added the effect of solid-solid conduction. The gas in the gap may be flushed in a refabrication step. (See also `PlenumPressure` (10.8).)

```
[ThermalContact]
[./thermalcontact]
  type = GapHeatTransferLWR
  contact_coef = <real> (10)
  contact_pressure = <string>
  disp_x = <variable>
  disp_y = <variable>
  disp_z = <variable>
  emissivity_1 = <real> (0)
  emissivity_2 = <real> (0)
  external_pressure = <real> (0)
  initial_gas_fractions = <real list> (1 0 0 0 0 0 0 0 0 0)
  initial_moles = <string>
  gas_released = <string list>
  gas_released_fractions = <real list> (0 0 0.153 0.847 0 0 0 0 0 0)
  jump_distance_fuel = <real> (0)
  jump_distance_clad = <real> (0)
  jump_distance_model = <string> (DIRECT)
  master = <string>
```

```

meyer_hardness <real> (0.68e9)
min_gap = <real> (1e-6)
max_gap = <real> (1e6)
normal_smoothing_distance = <real>
normal_smoothing_method = <string> (edge_based)
order = <string> (FIRST)
quadrature = <bool> (false)
refab_gas_fractions = <real list>
refab_time = <real list>
refab_type = <integer list>
roughness_fuel = <real> (1e-6)
roughness_clad = <real> (1e-6)
roughness_coef = <real> (1.5)
interaction_layer = <integer> (0)
slave = <string>
stefan_boltzmann = <real> (5.669e-8)
tangential_tolerance = <real>
variable = <string>
[../]
[]

```

type	GapHeatTransferLWR
contact_coef	The leading coefficient on the solid-solid conduction relation ($1/\sqrt{m}$).
contact_pressure	The contact pressure variable. Typically contact_pressure.
disp_x	Variable name for displacement variable in x direction. Typically disp_x. Optional.
disp_y	Variable name for displacement variable in y direction. Typically disp_y. Optional.
disp_z	Variable name for displacement variable in z direction. Typically disp_z. Optional.
emissivity_1	The emissivity of the fuel surface.
emissivity_2	The emissivity of the cladding surface.
external_pressure	The external (gas) pressure.
initial_gas_fractions	The initial fractions of constituent gases (helium, argon, krypton, xenon, hydrogen, nitrogen, oxygen, carbon monoxide, carbon dioxide, water vapor).
initial_moles	The Postprocessor that will give the initial moles of gas.
gas_released	List of one or more Postprocessors that give the gas released.

<code>gas_released_fractions</code>	The fraction of released gas that is assigned to helium, argon, krypton, xenon, hydrogen, nitrogen, oxygen, carbon monoxide, carbon dioxide, and water vapor. One set of fractions for each <code>Postprocessor</code> listed in <code>gas_released</code> .
<code>jump_distance_fuel</code>	The temperature jump distance of the fuel.
<code>jump_distance_clad</code>	The temperature jump distance of the clad.
<code>jump_distance_model</code>	One of <code>DIRECT</code> (specify distances directly) or <code>KENNARD</code> (jump distances computed based on gas properties).
<code>master</code>	The boundary id for the master surface.
<code>meyer_hardness</code>	The Meyer hardness of the softer material (Pa).
<code>min_gap</code>	The minimum permissible gap size.
<code>max_gap</code>	The maximum permissible gap size.
<code>normal_smoothing_distance</code>	Distance from face edge in parametric coordinates over which to smooth the contact normal. 0.1 is a reasonable value.
<code>normal_smoothing_method</code>	One of <code>edge_based</code> or <code>nodal_normal_based</code> . If <code>nodal_normal_based</code> , must also have a <code>NodalNormals</code> block.
<code>order</code>	The order of the variable. Typical values are <code>FIRST</code> and <code>SECOND</code> .
<code>plenum_pressure</code>	The name of the plenum pressure <code>Postprocessor</code> .
<code>quadrature</code>	Whether or not to use quadrature point-based gap heat transfer.
<code>refab_gas_fractions</code>	The fractions of constituent gases at refabrication (helium, argon, krypton, xenon, hydrogen, nitrogen, oxygen, carbon monoxide, carbon dioxide, water vapor).
<code>refab_time</code>	The time(s) at which refabrication occurs. If multiple times are given, multiple sets of <code>refab_gas_fractions</code> and multiple <code>refab_types</code> must be given.
<code>refab_type</code>	One of 0 (instantaneous reset, evolving gas fraction thereafter) or 1 (instantaneous reset, constant gas fraction thereafter).
<code>roughness_fuel</code>	The roughness of the fuel surface.
<code>roughness_clad</code>	The roughness of the cladding surface.
<code>roughness_coef</code>	The coefficient for the roughness summation.
<code>interaction_layer</code>	One of 0 (fuel-cladding chemical interaction layer not considered) and 1 (interaction layer considered).
<code>slave</code>	The boundary id for the slave surface.
<code>stefan_boltzmann</code>	The Stefan-Boltzmann constant.

tangential_tolerance
variable

Tangential distance to extend edges of contact surfaces.
Required. The temperature variable name.

12 AuxKernels

AuxKernels are used to compute values for AuxVariables. They often compute quantities based on functions, solution variables, and material properties. AuxKernels can apply to blocks or boundaries. If not block or boundary is specified, the AuxKernel applies to the entire model.

```
[AuxKernels]
  [./name]
    type = <AuxKernel type>
    block = <string list>
    boundary = <string list>
    ...
  [../]
[]
```

type Type of auxiliary kernel.
block List of blocks. Either block numbers or names.
boundary List of boundaries (side sets). Either boundary numbers or names.

12.1 AuxKernels for Output

12.1.1 MaterialRealAux

The MaterialRealAux AuxKernel is used to output material properties. Typically, the Aux-Variable computed by MaterialTensorAux will be an element-level, constant variable. The computed value will be the volume-averaged quantity over the element.

```
[./materialrealaux]
  type = MaterialRealAux
  property = <material property>
  variable = <variable>
[../]
```

type MaterialRealAux
property **Required.** Name of material property.
variable **Required.** Name of AuxVariable that will hold result.

12.1.2 MaterialTensorAux

The `MaterialTensorAux` `AuxKernel` is used to output quantities related to second-order tensors used as material properties. Stress and strain are common examples of these tensors. The `AuxKernel` allows output of specific tensor entries or quantities computed from the entire tensor. Typically, the `AuxVariable` computed by `MaterialTensorAux` will be an element-level, constant variable. By default, the computed value will be the volume-averaged quantity over the element. If the parameter `qp_select` is set to the value of an integration point number (0, 1, ..., n), the computed value will be the value at that integration point.

```
[./materialtensoraux]
  type = MaterialTensorAux
  tensor = <material property tensor>
  variable = <variable>
  index = <integer>
  quantity = <string>
  point1 = <vector> (0, 0, 0)
  point2 = <vector> (0, 1, 0)
  qp_select = <integer> (0, 1, ..., n)
[../]
```

<code>type</code>	<code>MaterialTensorAux</code>
<code>tensor</code>	Required. Name of second-order tensor material property. A typical second-order tensor material property is <code>stress</code> .
<code>variable</code>	Required. Name of <code>AuxVariable</code> that will hold result.
<code>index</code>	Index into tensor, from 0 to 5 (xx, yy, zz, xy, yz, zx). Either <code>index</code> or <code>quantity</code> must be specified.
<code>quantity</code>	One of <code>VonMises</code> , <code>PlasticStrainMag</code> , <code>Hydrostatic</code> , <code>Hoop</code> , <code>Radial</code> , <code>Axial</code> , <code>MaxPrincipal</code> , <code>MedPrincipal</code> , <code>MinPrincipal</code> , <code>FirstInvariant</code> , <code>SecondInvariant</code> , <code>ThirdInvariant</code> , or <code>TriAxiality</code> . Either <code>index</code> or <code>quantity</code> must be specified.

12.2 AuxKernels for Specifying Fission Rate

Note that these `AuxKernels` are not needed if the `Burnup` block (see Chapter 13) is present.

12.2.1 FissionRateAux

The `FissionRateAux` `AuxKernel` simply sets the value of a variable that stores the fission rate (fissions/m³/s) to either a constant value or a value prescribed by a function. If both `function` and `value` are provided, `value` is used as a scaling factor on the function.

```
[./fissionrateaux]
  type = FissionRateAux
  variable = <string>
```

```

    block = <string list>
    function = <string>
    value = <real>
    variable = <string>
[../]

```

type FissionRateAux
 variable **Required.** Name of AuxVariable that will hold fission rate. Typically fission_rate.
 value Value of fission rate. If function is present, value is multiplied by the function value.
 function Function describing the fission rate.

12.2.2 FissionRateAuxLWR

FissionRateAuxLWR is designed to calculate fission rate given rod averaged linear power and pellet dimensions.

```

[./fissionrateauxlwr}
  type = FissionRateAuxLWR
  value = <real> (1)
  rod_ave_lin_pow= <string>
  axial_power_profile = <string>
  pellet_diameter = <real>
  pellet_inner_diameter = <real> (0)
  fuel_volume_ratio = <real> (1)
  energy_per_fission = <real> (3.28451e-11)
  variable = <string>
[../]

```

value Fission rate if rod_ave_lin_pow is not present. Scale factor if rod_ave_lin_pow is given.
 variable **Required.** Name of AuxVariable that will hold fission rate. Typically fission_rate.
 rod_ave_lin_pow Function describing rod averaged linear power. This power is the total power, the power from the volumetric fission rate times the volume of fuel times the energy per fission.
 axial_power_profile Function describing axial power profile.
 pellet_diameter **Required.** The diameter of the fuel.
 pellet_inner_diameter The inner diameter of the fuel.
 fuel_volume_ratio Reduction factor for deviation from right circular cylinder fuel. The ratio of actual volume to right circular cylinder volume.
 energy_per_fission The energy released per fission in J/fission.

12.2.3 FissionRateFromPowerDensity

Like `FissionRateAux`, the `FissionRateFromPowerDensity` `AuxKernel` sets the fission rate based on a function and a scaling factor. This `AuxKernel` is intended to be used specifically in the case where the input function defines the power density (in W/m^3). The power density is divided by user-provided constant that defines the energy per fission ($\text{J}/\text{fission}$) to provide the fission rate in ($\text{fissions}/\text{m}^3/\text{s}$).

```
[./fissionratefrompowerdensity]
  type = FissionRateFromPowerDensity
  variable = <string>
  block = <string list>
  function = <string>
  energy_per_fission = <real>
[../]
```

<code>type</code>	<code>FissionRateAux</code>
<code>variable</code>	Required. Name of <code>AuxVariable</code> that will hold fission rate. Typically <code>fission_rate</code> .
<code>function</code>	Required. Function describing the power density in W/m^3 .
<code>energy_per_fission</code>	Required. Energy released per fission in $\text{J}/\text{fission}$.

12.3 Other AuxKernels

12.3.1 Al2O3Aux

```
[./al2o3aux]
  type = Al2O3Aux
  variable = <string>
  function = <string>
  model = <string> (function)
  temp = <string>
[../]
```

<code>type</code>	<code>Al2O3Aux</code>
<code>variable</code>	Required. Variable name corresponding to the Al_2O_3 thickness.
<code>function</code>	Function describing the Al_2O_3 thickness as a function of time.
<code>model</code>	One of <code>function</code> or <code>griess</code> . The <code>griess</code> option invokes a correlation appropriate for plate fuel.
<code>temp</code>	Variable name for temperature variable. Typically <code>temp</code> .

12.3.2 BurnupAux

BurnupAux computes burnup given the fission rate. Note that this AuxKernel is not needed if the Burnup block (see Chapter 13) is present.

```
[./burnupaux]
  type = BurnupAux
  fission_rate = <string>
  density = <real>
  molecular_weight = <real> (0.270)
[../]
```

type	BurnupAux
variable	Required. Variable name corresponding to the burnup. Typically burnup.
fission_rate	Required. Variable name corresponding to the fission rate. Typically fission_rate.
density	Required. The initial fuel density.
molecular_weight	The molecular weight.

12.3.3 FastNeutronFluenceAux

```
[./fastneutronfluenceaux]
  type = FastNeutronFluenceAux
  variable = <string>
  fast_neutron_flux = <string>
[../]
```

type	FastNeutronFluenceAux
variable	Required. Variable name corresponding to the fast neutron fluence. Typically fast_neutron_fluence.
fast_neutron_flux	Required. Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.

12.3.4 FastNeutronFluxAux

```
[./fastneutronfluxaux]
  type = FastNeutronFluxAux
  variable = <string>
  rod_ave_lin_pow = <string>
  axial_power_profile = <string>
  factor = <real>
  function = <string>
  q_variable = <string>
```

```
[../]
```

type	FastNeutronFluxAux
variable	Required. Variable name corresponding to the fast neutron flux. Typically <code>fast_neutron_flux</code> .
rod_ave_lin_pow	Function describing rod averaged linear power. This power is the total power, the power from the volumetric fission rate times the volume of fuel times the energy per fission.
axial_power_profile	Function describing axial power profile.
factor	The fast neutron flux if function, <code>rod_ave_lin_pow</code> , or <code>q_variable</code> is not given. Otherwise, a scale factor. Recommended scale factor value is $3e13$ (n/(m ² -s)/(W/m)).
function	Function that describes the fast neutron flux.
q_variable	Variable holding linear heat rate in pellet in W/m.

Only one of `function`, `rod_ave_lin_pow`, and `q_variable` may be given.

12.3.5 GrainRadiusAux

The `GrainRadiusAux` model is a simple empirical model for calculating grain growth. This can be used with the `Sifgrs` model (17.1).

```
[./grainradiusaux]
  type = GrainRadiusAux
  variable = <string>
  temp = <string>
[../]
```

type	GrainRadiusAux
variable	Required. Variable name corresponding to the fuel grain radius.
temp	Required. Variable name for temperature variable. Typically <code>temp</code> .

12.3.6 OxideAux

```
[./oxideaux]
  type = OxideAux
  variable = <string>
  fast_neutron_flux = <string>
  lithium_concentration = <real> (0)
  model_option = <int> (1)
  oxide_scale_factor = <real> (1)
  tin_content = <real> (1.38)
  temperature = <string>
```

```

use_coolant_channel = <bool> (false)
start_time = <real> (0)
end_time = <real> (inf)

```

type	OxideAux
variable	Required. Variable name corresponding to the zirconia thickness.
fast_neutron_flux	Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.
lithium_concentration	Lithium concentration in ppm.
model_option	If 1, uses the EPRI KWU CE model. Otherwise, uses the EPRI SLI model.
oxide_scale_factor	Scale factor applied to the rate of oxide growth.
tin_content	Tin content in wt%.
temperature	Required. Variable name for temperature variable. Typically temp.
use_coolant_model	If true, model will adjust surface temperature based on the coolant channel model.
start_time	Start the oxide growth at a specific time.
end_time	End the oxide growth at a specific time, for example in dry storage.

12.3.7 PelletIdAux

PelletIdAux is used to compute a pellet number. It may be used with a discrete pellet or smeared fuel column mesh.

```

[./pelletidaux]
type = PelletIdAux
variable = <string>
a_lower = <real>
a_upper = <real>
number_pellets = <integer>
[../]

```

type	PelletIdAux
variable	Required. AuxVariable name corresponding to the Pellet ID.
a_lower	Required. The lower axial coordinate of the fuel stack.
a_upper	Required. The upper axial coordinate of the fuel stack.
number_pellets	Required. Number of fuel pellets.

13 Burnup

The `Burnup` block computes fission rate and burnup for LWR fuel including the radial power factor. It is not appropriate for other fuel configurations. Use of the `Burnup` block will cause BISON to create and populate `burnup`, `fission_rate`, and optionally other `AuxVariables`.

The radial power factor calculation is performed on a secondary numerical grid, created internally by BISON. This is the reason for the `num_radial` and `num_axial` line commands. Once the fission rate, burnup, and other quantities are computed on this secondary grid, they are mapped back to the finite element mesh.

```
[Burnup]
  [./burnup]
    block = <string list>
    rod_ave_linear_power = <string>
    axial_power_profile = <string>
    num_radial = <integer>
    num_axial = <integer>
    fuel_pin_geometry = <string>
    a_lower = <real>
    a_upper = <real>
    fuel_inner_radius = <real> (0)
    fuel_outer_radius = <real> (0.0041)
    fuel_volume_ratio = <real> (1)
    density = <real>
    energy_per_fission = <real> (3.28451e-11)
    p1 = <real> (3.45)
    i_enrich = <real list> (0.05, 0.95, 0, 0, 0, 0)
    sigma_c = <real list> (9.7, 0.78, 58.6, 100, 50, 80)
    sigma_f = <real list> (41.5, 0, 105, 0.584, 120, 0.458)
    sigma_a_thermal = <real list> (sum of sigma_c and sigma_f)
    reactor_type = <string> (LWR)
    N235 = <string>
    N238 = <string>
    N238 = <string>
    N240 = <string>
    N241 = <string>
    N242 = <string>
    RPF = <string>
  [../]
[]
```

`block`

Required. List of fuel blocks. Either block numbers or names.

rod_ave_lin_pow	Function describing rod averaged linear power. This power is the total power, the power from the volumetric fission rate times the volume of fuel times the energy per fission.
axial_power_profile	Function describing axial power profile.
num_radial	Number of radial divisions in secondary grid used to compute radial power profile.
num_axial	Number of axial divisions in secondary grid used to compute radial power profile.
fuel_pin_geometry	Name of the FuelPinGeometry object (see 23.1).
a_lower	Required if fuel_pin_geometry is not specified. The lower axial coordinate of the fuel stack.
a_upper	Required if fuel_pin_geometry is not specified. The upper axial coordinate of the fuel stack.
fuel_inner_radius	The inner radius of the fuel.
fuel_outer_radius	The outer radius of the fuel.
fuel_volume_ratio	Reduction factor for deviation from right circular cylinder fuel. The ratio of actual volume to right circular cylinder volume.
density	Required. The initial fuel density.
energy_per_fission	The energy released per fission in J/fission.
p1	Distribution function coefficient p1. If not given, will take default value based on reactor_type.
i_enrich	The initial enrichment for the six isotopes.
sigma_c	The capture cross sections for the six isotopes. If not given, will take default value based on reactor_type.
sigma_f	The fission cross sections for the six isotopes. If not given, will take default value based on reactor_type.
sigma_a_thermal	The absorption (thermal) cross sections for the six isotopes.
reactor_type	Reactor type. One of LWR or HWR. Will set default values for p1, sigma_f, and sigma_c if those are not otherwise specified.
N235	Indicates that the output of the concentration of N235 is required. Typically N235.
N238	Indicates that the output of the concentration of N238 is required. Typically N238.
N239	Indicates that the output of the concentration of N239 is required. Typically N239.
N240	Indicates that the output of the concentration of N240 is required. Typically N240.
N241	Indicates that the output of the concentration of N241 is required. Typically N241.

N242	Indicates that the output of the concentration of N242 is required. Typically N242.
RPF	Indicates that the output of the radial power factor is required. Typically RPF.

14 Kernels

Kernels are used to evaluate integrals associated with a given term in a PDE. They often compute quantities based on functions, solution variables, auxiliary variables, and material properties. All Kernels act on blocks. If no block is specified, the Kernel will act on the entire model.

```
[Kernels]
  [./name]
    type = <kernel type>
    block = <string list>
    ...
  [../]
[]
```

type Type of kernel.

block List of blocks. Either block numbers or names.

14.1 Arrhenius Diffusion

Kernel for applying an Arrhenius diffusion term. If present, an ArrheniusDiffusionCoef material model must also be present.

```
[./arrheniusdiffusion]
  type = ArrheniusDiffusion
  variable = <variable>
[../]
```

type ArrheniusDiffusion

variable **Required.** Variable associated with this volume integral.

14.2 BodyForce

Kernel for applying an arbitrary body force to the model.

```
[./bodyforce]
  type = BodyForce
  variable = <variable>
  value = <real> (0)
```

```
function = <string> (1)
[../]
```

type BodyForce
variable **Required.** Variable associated with this volume integral.
value Constant included in volume integral. Multiplied by the value of function if present.
function Function to be multiplied by value and used in the volume integral.

14.3 Gravity

Gravity may be applied to the model with this kernel. The required density is computed and provided internally given inputs in the `Materials` block.

```
[./gravity]
type = Gravity
variable = <variable>
value = <real> (0)
[../]
```

type Gravity
variable **Required.** Variable name corresponding to the displacement direction in which the gravity load should be applied.
value Acceleration of gravity. Typically -9.81 (m/s²).

14.4 Heat Conduction

Kernel for diffusion of heat or divergence of heat flux.

```
[./heatconduction]
type = HeatConduction
variable = <variable>
[../]
```

type HeatConduction
variable **Required.** Variable name corresponding to the heat conduction equation. Typically `temp`.

14.5 Heat Conduction Time Derivative

Kernel for $\rho C_p \partial T / \partial t$ term of the heat equation.

```
[./heatconductiontimederivative]
  type = HeatConductionTimeDerivative
  variable = <variable>
[../]
```

type HeatConductionTimeDerivative
variable **Required.** Variable name corresponding to the heat conduction equation. Typically temp.

14.6 Heat Source

The `HeatSource` kernel applies a volumetric heat source to specified blocks within the model. Built on the `BodyForce` kernel's code, the `HeatSource` kernel provides a more relevant name for easier input-file specification.

```
[./heatsource]
  type = HeatSource
  variable = <variable>
  value = <real> (1)
  function = <string> (1)
  block = <string list>
[../]
```

type HeatSource
variable **Required.** The variable associated with the heat source.
value Value of the heat source; will be multiplied by the optional function.
function The function describing the volumetric heat source.
block The list of block id's (SubdomainID) to which the heat source will be applied.

14.7 Isotropic Diffusion

`IsotropicDiffusion` is just like `ArrheniusDiffusion` except that it takes an arbitrary material property and uses it as the diffusivity. For example, it could be coupled to the material property `ArrheniusDiffusionCoef` using the material property "arrhenius_diffusion_coef" or to `ArrheniusMaterialProperty` using any name for the diffusivity.

```
[./diffusion]
  type = IsotropicDiffusion
  variable = <variable>
  diffusivity_property = <string> (diffusivity)
[../]
```

type	IsotropicDiffusion
variable	Required. Variable associated with this volume integral.
diffusivity_property	The name of the material property to be used as the diffusivity.

14.8 Neutron Heat Source

Kernel for the volumetric heat source associated with fission.

```
[./neutronheatsource]
  type = NeutronHeatSource
  variable = <variable>
  burnup_function = <string>
  fission_rate = <variable>
  decay_heat_function = <string>
  fuel_pin_geometry = <string>
  outer_diameter = <real>
  inner_diameter = <real> (0)
  area = <real>
[../]
```

type	NeutronHeatSource
variable	Required. Variable name corresponding to the heat conduction equation. Typically temp.
burnup_function	Name of the Burnup sub-block, if any (typically burnup). May not be used with fission_rate. Use of burnup_function is preferred.
fission_rate	Variable name corresponding to the fission rate. Typically fission_rate.
decay_heat_function	Name of the postprocessor giving the decay heat curve. Typically supplied for LOCA simulations.
fuel_pin_geometry	Name of the FuelPinGeometry object (see 23.1).
outer_diameter	Outer diameter of the cold fuel pellets if fuel_pin_geometry is not specified.
inner_diameter	Inner diameter of the cold fuel pellets if fuel_pin_geometry is not specified.
area	Cross-sectional area of the cold fuel pellets if fuel_pin_geometry or the diameters are not specified.

14.9 SolidMechanics

The SolidMechanics block specifies inputs for the divergence of stress as part of the equations of solid mechanics. The divergence of stress is a Kernel in MOOSE nomenclature. The

SolidMechanics block informs MOOSE of the divergence kernels but is not placed inside the Kernels block in the input file.

```
[SolidMechanics]
  [./solidmechanics]
    disp_x = <variable>
    disp_y = <variable>
    disp_z = <variable>
    disp_r = <variable>
    temp = <variable>
  [../]
[]
```

- disp_x Variable name for displacement variable in x direction. Typically disp_x.
- disp_y Variable name for displacement variable in y direction. Typically disp_y.
- disp_z Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
- disp_r Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
- temp Variable name for temperature variable. Necessary for thermal expansion. Typically temp.

14.10 Thermo-diffusion (Soret effect, thermophoresis)

ThermoDiffusion is used to model mass flux of the form

$$J = -\frac{DQC}{RT^2}\nabla T \tag{14.1}$$

where D is the mass diffusivity (property name is “mass_diffusivity”), Q is the heat of transport, C is the concentration, R is the gas constant, and T is the temperature.

```
[./soret_diffusion]
  type = ThermoDiffusion
  variable = <variable>
  temp = <variable>
  gas_constant = <real> (8.31446)
[../]
```

- type ThermoDiffusion
- variable **Required.** Variable associated with this volume integral.
- temp **Required.** Coupled temperature variable.
- gas_constant Universal gas constant.

14.11 TimeDerivative

Kernel for applying a time rate of change term ($\partial u/\partial t$) to the model.

```
[./timederivative]
  type = TimeDerivative
  variable = <variable>
[../]
```

type TimeDerivative

variable **Required.** Variable associated with this volume integral.

15 Hydride formation in the cladding

Modeling the evolution of hydrides in the cladding requires two variables to track concentration of the hydrogen in solution and the hydrogen as hydride, kernels that act as source/sink terms for the concentration variables, kernels for Fickian and thermal diffusion of the hydrogen, a kernel for the time derivative of hydrogen, and a set of material models that calculate precipitation and dissolution rates, and the heat of transport and diffusivity of hydrogen. In addition, if hydrogen pickup is of interest, a corrosion model and pickup boundary condition must be added. However, there is also an Action that sets up everything except for the two variables and the hydrogen pickup; we cover the variables and the Action first.

15.1 Using the CladdingHydrides Action (the easy way)

The two concentration variables track the hydrogen in solid solution (commonly referred to as C_{ss}) and the equivalent concentration of hydrogen bound in the precipitated hydrides (commonly referred to as C_p). These concentrations are usually specified in ppm by weight. Since the hydride may have a steep gradient, monomials are helpful to keep the concentration positive. Also note below the large scalings that are useful for speeding convergence.

```
[Variables]
  [./hydrogen_in_solution_ppm]
    scaling = 1e12
    block = 'clad'
  [../]
  [./hydrogen_as_hydride_ppm]
    order = CONSTANT
    family = MONOMIAL
    scaling = 1e12
    block = 'clad'
  [../]
[]
```

The CladdingHydrides Action adds Fick's Law, the Soret effect, a precipitation/dissolution sink/source term, and a specialized time derivative for soluble hydrogen. It also adds a precipitation/dissolution source/sink term and a time derivative for hydrogen as hydride. These kernels require a few specialized material models for the actual precipitation/dissolution rate, the mass diffusivity of hydrogen in the matrix, and the heat of transport for hydrogen; these are also added by the Action. Thus, if you use this Action and have the variables listed above, then you only need to add a hydrogen pickup boundary condition (see 10.7) to get the complete hydride model for the cladding.

```
[CladdingHydrides]
  [./some_name]
    block = <list of blocks>
    temperature = <string>
    hydrogen_in_solution_ppm = <string>
    hydrogen_as_hydride_ppm = <string>
    hydride_clamp = <real> (1)
    diffusivity_frequency_factor = <real> (0.8e-7)
    diffusivity_activation_energy = <real> (33306)
    heat_of_transport = <real> (25121)
  [../]
[]
```

block	List of blocks where the hydride model is to be applied (the cladding blocks).
temperature	Required. Name of the temperature variable.
hydrogen_in_solution_ppm	Required. Name of the variable for hydrogen in solution (wt.ppm).
hydrogen_as_hydride_ppm	Required. Name of the variable for hydrogen as hydrides (wt.ppm).
hydride_clamp	The limiting value of the volume fraction of hydrides. This is used to control creation of a thick hydride rim. Must be in [0,1].
diffusivity_frequency_factor	The Arrhenius coefficient for hydrogen mass diffusivity in the cladding.
diffusivity_activation_energy	The Arrhenius activation energy for hydrogen mass diffusivity in the cladding.
heat_of_transport	The heat of transport for dissolved hydrogen in the cladding.

15.2 Using individual kernels and materials (the hard way)

15.2.1 HydridePrecipitationRate

A single material is used to calculate the precipitation or dissolution rate. This is not a material property *per se*; it is just used this way for convenience.

```
[Materials]
  [./precip_rate]
    type = HydridePrecipitationRate
    block = <string>
    temp = <variable>
    hydrogen_in_solution_ppm = <variable>
```

```

hydrogen_as_hydride_ppm = <variable>
hydride_clamp = <real> (1)
[../]
[]

```

type	HydridePrecipitationRate
block	The volume associated with this material.
temp	Required. Coupled temperature variable.
hydrogen_in_solution_ppm	Required. Coupled C_{ss} in wt.ppm.
hydrogen_as_hydride_ppm	Required. Coupled C_p in wt.ppm.
hydride_clamp	The limiting value of the volume fraction of hydrides. This is used to control creation of a thick hydride rim. Must be in [0,1].

The clamping feature is used to limit the amount of hydride that forms by precipitation. If the hydride concentration exceeds the clamp value, the local rate of hydride precipitation will drop to zero even if there is local over saturation of hydrogen in solid solution.

15.2.2 HydrogenSource and HydrideSource

Finally, we just need to add two source kernels: one for C_{ss} and one for C_p . The kernel is a source if precipitation increases the concentration or a sink if precipitation decreases the concentration (i.e. precipitation is a sink for hydrogen in solid solution). For convenience, these are split into HydrogenSource and HydrideSource so that the user does not have to keep track of the sign on the source term.

```

[Kernels]
  [./hydride_source]
    type = HydrideSource
    variable = <variable>
  [../]
[]

```

type	HydrideSource
variable	Required. The concentration of hydrogen in one of the phases.

HydrogenSource has the same form as HydrideSource (only the type changes).

15.2.3 HydrogenTimeDerivative

Due to the special treatment of the hydrogen in solution (a volume fraction term appears in the time derivative), we need a special kernel for this term. It needs to couple into the hydride variable as well.

```
[Kernels]
  [./hydrogen_dHdt]
    type = HydrogenTimeDerivative
    variable = <variable>
    hydrogen_as_hydride_ppm = <string>
  [../]
[]
```

type	HydrogenTimeDerivative
variable	Required. The concentration of hydrogen in solution (wt.ppm).
hydrogen_as_hydride_ppm	Required. The concentration of hydrogen as hydrides (wt.ppm).
hydrider_clamp	The limiting value of the volume fraction of hydrides. This is used to control creation of a thick hydrider rim. Must be in [0,1].

15.2.4 HydrogenDiffusivity

Similarly to HydrogenTimeDerivative, the diffusion term for the hydrogen in solution must also account for the phase fraction of alloy that is available for diffusion.

```
[Materials]
  [./hydrogen_diffusivity]
    type = HydrogenDiffusivity
    frequency_factor = <real>
    activation_energy = <real>
    temp = <string>
    property_name = <string>( 'mass_diffusivity' )
    hydrogen_as_hydrider_ppm = <string>
    hydrider_clamp = <real> (1)
  [../]
[]
```

type	HydrogenDiffusivity
frequency_factor	Arrhenius frequency factor.
activation_energy	Arrhenius activation energy.
temp	Required. The coupled temperature.
property_name	The named property that will be declared by this material.
hydrogen_as_hydrider_ppm	Required. The concentration of hydrogen as hydrides (wt.ppm).

hydride_clamp

The limiting value of the volume fraction of hydrides. This is used to control creation of a thick hydride rim. Must be in [0,1].

15.2.5 Other things needed for modeling hydrides without the CladdingHydrides Action

The kernels and materials for simulating the transport of the hydrogen in solution are generic kernels and are not covered here; see 14.7 for mass diffusion and 14.10 for the Soret effect. These two kernels require material properties for mass diffusivity (use `HydrogenDiffusivity`) and heat of transport of hydrogen (use `GenericConstantMaterial` and name the property “heat_of_transport”) in the alloy. Also not shown here is the flux boundary condition for hydrogen pickup at the oxide interface (see 10.7).

16 Materials

The Materials block is for specifying material properties and models.

```
[Materials]
  [./name]
    type = <material type>
    block = <string list>
    ...
  [../]
[]
```

- type Type of material model
- block List of blocks. Either block numbers or names.

16.1 Thermal Models

16.1.1 HeatConductionMaterial

HeatConductionMaterial is a general-purpose material model for heat conduction. It sets the thermal conductivity and specific heat at integration points.

```
[./heatconductionmaterial]
  type = HeatConductionMaterial
  thermal_conductivity = <real>
  thermal_conductivity_x = <string>
  thermal_conductivity_y = <string>
  thermal_conductivity_z = <string>
  thermal_conductivity_temperature_function = <string>
  specific_heat = <real>
  specific_heat_temperature_function = <string>
[../]
```

- | | |
|------------------------|--|
| type | HeatConductionMaterial |
| thermal_conductivity | Thermal conductivity. |
| thermal_conductivity_x | Thermal conductivity Postprocessor for the x direction. |
| thermal_conductivity_y | Thermal conductivity Postprocessor for the y direction. |

<code>thermal_conductivity_z</code>	Thermal conductivity Postprocessor for the z direction.
<code>thermal_conductivity_temperature_function</code>	Function describing thermal conductivity as a function of temperature.
<code>specific_heat</code>	Specific heat.
<code>specific_heat_temperature_function</code>	Function describing specific heat as a function of temperature.

16.1.2 ThermalCladMaterial

The `ThermalCladMaterial` model computes the specific heat and thermal conductivity for a variety of exotic cladding materials. The choices are `Thermal316`, `ThermalAlloy33`, `ThermalD9`, `ThermalHT9`, `ThermalIrradiationCreepHT9`, `ThermalMo`, and `ThermalNa`. The details of these models are described in the Theory Manual. Examples of their use can be found in `/bison/tests/thermalTests/`, `/bison/tests/thermalD9/`, `/bison/tests/thermalNa/`, and `/bison/tests/thermalHT9/`.

```
[./thermalCladMaterial]
  type = Thermal<string>
  block = <string list>
  temp = <string>
[../]
```

- `type` `Thermal<string>`, where `<string>` is the fuel material type (eg. HT9)
- `block` List of blocks this material applies to.
- `temp` Name of temperature variable. Typically `temp`.

16.1.3 ThermalFeCrAl

The `ThermalFeCrAl` model computes the specific heat and thermal conductivity for a variety of FeCrAl cladding alloys. The alloys to choose from are Special Metals Incoloy MA956, Plansee PM2000, Kanthal APMT and Resistalloy International Fecralloy.

```
[./thermalFeCrAl]
  type = ThermalFeCrAl
  block = <string list>
  material = <string>
  temp = <string>
[../]
```

- `type` `ThermalFeCrAl`
- `block` List of blocks this material applies to.
- `material` Name of the chosen FeCrAl alloy. Choices are MA956, PM2000, APMT or FECRALLOY

temp Name of temperature variable. Typically temp.

16.1.4 ThermalFuel

The ThermalFuel model computes specific heat and thermal conductivity for oxide fuel. A number of correlations are available.

```
[./thermalfuel]
type = ThermalFuel
temp = <string>
burnup_function = <string>
burnup = <string>
porosity = <string>
initial_porosity = <real> (0.05)
oxy_to_metal_ratio = <real> (2.0)
Pu_content = <real> (0.0)
Gd_content = <real> (0.0)
model = < 0, 1, 2, 3, 4, or 5 for
          Duriez, Amaya, Fink-Lucuta, Halden, NFIR, or Modified NFIR >
[../]
```

type	ThermalFuel
temp	Name of temperature variable. Typically temp.
burnup_function	Name of the Burnup sub-block, if any (typically burnup). May not be used with the burnup line command. Use of burnup_function is preferred.
burnup	Name of burnup variable. Typically burnup.
porosity	Name of porosity variable. Typically porosity. Optional.
initial_porosity	Initial porosity.
oxy_to_metal_ratio	Ratio of oxygen atoms to metal atoms.
Pu_content	Weight fraction of Pu in MOX fuel (typically 0.07).
Gd_content	Weight fraction of Gd in fuel.
model	Required. The chosen thermal conductivity model.

16.1.5 ThermalFastMOX

The ThermalFastMOX model computes the thermal conductivity for fast MOX fuel. Currently a single correlation is available from Inoue and used by Karahan. Details are provided in the theory manual. The specific heat capacity is treated as a constant value for now.

```
[./thermalfastmox]
type = ThermalFastMOX
temp = <string>
burnup_function = <string>
```

```

burnup = <string>
porosity = <string>
initial_porosity = <real> (0.05)
oxy_to_metal_ratio = <real> (2.0)
[../]

```

type	ThermalFastMOX
temp	Name of temperature variable. Typically temp.
burnup_function	Name of the Burnup sub-block, if any (typically burnup). May not be used with the burnup line command. Use of burnup_function is preferred.
burnup	Name of burnup variable. Typically burnup.
porosity	Name of porosity variable. Typically porosity. Optional.
initial_porosity	Initial porosity.
oxy_to_metal_ratio	Ratio of oxygen atoms to metal atoms.

16.1.6 ThermalFuelMaterial

The ThermalFuelMaterial model computes specific heat and thermal conductivity for a variety of exotic fuel materials. The choices are ThermalU, ThermalU10Mo, ThermalU3Si2. The details of these models are described in the Theory Manual. Examples of their use can be found in /bison/tests/thermalTests/.

```

[./thermalFuelMaterial]
type = Thermal<string>
block = <string list>
temp = <string>
porosity = <string>
density = <real>
[../]

```

type	Thermal<string>, where <string> is the fuel material type (eg. U10Mo)
block	List of blocks this material applies to.
temp	Name of temperature variable. Typically temp.
porosity	Name of porosity variable. Typically porosity. Optional.
density	Required. Density, assumed constant.

16.1.7 ThermalUPuZr

The ThermalUPuZr model computes the specific heat and thermal conductivity for any alloy of U-Pu-Zr metal fuel. If porosity and porosity_material are both defined an error will result. The user has the choice of not supplying any porosity, supplying a variable for porosity or couple

to a material that calculates the porosity.

```
[./thermalUPuZr]
  type = ThermalUPuZr
  block = <string list>
  temp = <string>
  porosity = <string>
  porosity_material = <bool> (false)
  pu_weight = <real>
  zr_weight = <real>
[../]
```

type	ThermalUPuZr
block	List of blocks this material applies to.
temp	Name of temperature variable. Typically temp.
porosity	Name of porosity variable. Typically porosity. Optional.
porosity_material	A flag indicating whether porosity is being calculated by a material property (e.g., VSwellingUPuZr). Optional.
pu_weight	Required. The weight fraction of plutonium in the fuel. Given as a decimal (e.g., 0.2)
zr_weight	Required. The weight fraction of zirconium in the fuel. Given as a decimal (e.g., 0.15)

16.1.8 ThermalU3Si2

The ThermalU3Si2 model computes the specific heat and thermal conductivity for U₃Si₂ fuel. Two models are available for both thermal conductivity and specific heat. The details of these models can be found in the theory manual.

```
[./thermalU3Si2]
  type = ThermalU3Si2
  block = <string list>
  temp = <string>
  specific_heat_model = <string> (WHITE)
  thermal_conductivity_model = <string> (WHITE)
[../]
```

type	ThermalU3Si2
block	List of blocks this material applies to.
temp	Name of temperature variable. Typically temp.
porosity	Name of porosity variable. Typically porosity. Optional.
specific_heat_model	Name of the model to be used to compute the specific heat. Default is WHITE. Options are WHITE and IAEA.

thermal_conductivity_model Name of the model to be used to compute the thermal conductivity. Default is WHITE. Options are WHITE and SHIMIZU.

16.2 Solid Mechanics Models

16.2.1 CreepFastMOXModel

CreepFastMOXModel is used to model the creep behavior of fast MOX.

```
[./creepfastmox]
type = CreepFastMOXModel
absolute_tolerance = <real>
creeprate_scalef = <real>
fission_rate = <string>
fraction_of_temp_outside_model_bounds = <real>
grain_size = <real>
max_creep_increment = <real>
max_its = <int>
output = <string>
output_iteration_info = <bool>
output_iteration_info_on_error = <bool>
output_properties = <string>
outputs = <string>
relative_tolerance = <real>
stress_free_temperature = <real>
temp = <string>
thermal_expansion = <real>
thermal_expansion_coefficient = <real>
thermal_expansion_function = <string>
thermal_expansion_function_type = <string>
thermal_expansion_reference_temperature = <real>
use_displaced_mesh = <bool>
[../]
```

type	CreepFastMOXModel
absolute_tolerance	Absolute convergence tolerance for sub-newton iteration
creeprate_scalef	scaling factor for creep rate
fission_rate	Coupled fission rate
fraction_of_temp_outside_model_bounds	Fraction of temperature limit outside of model bounds
grain_size	grain size in micro meters
max_creep_increment	Maximum creep strain increment allowed by accuracy time step criterion

max_its	Maximum number of sub-newton iterations
output	The reporting postprocessor to use for the max_its value
output_iteration_info	Set true to output sub-newton iteration information
output_iteration_info_on_error	Set true to output sub-newton iteration information when a step fails
output_properties	List of material properties, from this material, to output (outputs must also be defined to an output type)
outputs	Vector of output names were you would like to restrict the output of variables(s) associated with this object
relative_tolerance	Relative convergence tolerance for sub-newton iteration
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.
temp	Coupled Temperature
thermal_expansion	The thermal expansion coefficient
thermal_expansion_function	Thermal expansion coefficient as a function of temperature
thermal_expansion_function_type	Type of thermal expansion function. Choices are: instantaneous mean
thermal_expansion_reference_temperature	Reference temperature for mean thermal expansion function

16.2.2 CreepPyC

CreepPyC is used to model the creep behavior of pyrolytic carbon.

```
[./creppyc]
type = CreepPyC
disp_x = <string>
disp_y = <string>
disp_z = <string>
disp_r = <string>
temp = <string>
flux = <string>
density = <real>
youngs_modulus = <real>
poissons_ratio = <real>
thermal_expansion = <real> (0)
stress_free_temperature = <real>
```

```
[../]
```

type	CreepPyC
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.
disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
flux	Required. Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.
density	Required. The initial material density.
thermal_expansion	Coefficient of thermal expansion.
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.

16.2.3 CreepSiC

```
[./creepsic]
type = CreepSiC
disp_x = <string>
disp_y = <string>
disp_z = <string>
disp_r = <string>
temp = <string>
fast_neutron_flux = <string>
k_function = <string>
youngs_modulus = <real>
poissons_ratio = <real>
thermal_expansion = <real> (0)
stress_free_temperature = <real>
[../]
```

type	CreepSiC
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.

disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
fast_neutron_flux	Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.
k_function	Required. Function that takes temperature as input and gives the K coefficient as output.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.
thermal_expansion	Coefficient of thermal expansion.
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.

CreepSiC is used to model the creep behavior of silicon carbide. The relation is

$$\dot{\epsilon}_{cr} = K\sigma\phi. \quad (16.1)$$

16.2.4 CreepU10Mo

CreepU10Mo is used to model the thermal and irradiation creep behavior of U-10Mo fast reactor fuel.

```
[./creepu10mo]
type = CreepU10Mo
disp_x = <string>
disp_y = <string>
disp_z = <string>
disp_r = <string>
temp = <string>
fission_rate = <string>
youngs_modulus = <real>
poissons_ratio = <real>
thermal_expansion = <real> (0)
stress_free_temperature = <real>
[../]
```

type	CreepU10Mo
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.

disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
fission_rate	Variable name corresponding to the fast neutron flux. Typically fission_rate.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.
thermal_expansion	Coefficient of thermal expansion.
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.

16.2.5 CreepUO2

The CreepUO2 is used to model the creep behavior of UO₂.

```

[./creepuo2]
  type = CreepUO2
  disp_x = <string>
  disp_y = <string>
  disp_z = <string>
  disp_r = <string>
  temp = <string>
  burnup_function = <string>
  fission_rate = <string>
  density = <real>
  youngs_modulus = <real>
  poissons_ratio = <real>
  thermal_expansion = <real> (0)
  grain_radius = <real> (10e-6)
  oxy_to_metal_ratio = <real> (2)
  relative_tolerance = <real> (1e-4)
  absolute_tolerance = <real> (1e-20)
  max_its = <integer> (10)
  output_iteration_info = <true or false> (false)
  stress_free_temperature = <real>
  matpro_youngs_modulus = <true or false> (false)
  matpro_poissons_ratio = <true or false> (false)
  matpro_thermal_expansion = <true or false> (false)
  burnup = <string>
[../]

```

type CreepUO2

<code>disp_x</code>	Variable name for displacement variable in x direction. Typically <code>disp_x</code> .
<code>disp_y</code>	Variable name for displacement variable in y direction. Typically <code>disp_y</code> .
<code>disp_z</code>	Variable name for displacement variable in z direction. Typically <code>disp_z</code> for 3D and <code>disp_y</code> for axisymmetric models.
<code>disp_r</code>	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically <code>disp_x</code> .
<code>temp</code>	Name of temperature variable. Typically <code>temp</code> .
<code>burnup_function</code>	Name of the Burnup sub-block, if any (typically <code>burnup</code>). May not be used with <code>fission_rate</code> . Use of <code>burnup_function</code> is preferred.
<code>fission_rate</code>	Variable name corresponding to the fission rate. Typically <code>fission_rate</code> .
<code>density</code>	Required. The initial fuel density.
<code>youngs_modulus</code>	Young's modulus.
<code>poissons_ratio</code>	Poisson's ratio.
<code>thermal_expansion</code>	Coefficient of thermal expansion.
<code>grain_radius</code>	Fuel grain radius.
<code>oxy_to_metal_ratio</code>	Oxygen to metal ratio.
<code>relative_tolerance</code>	Relative convergence tolerance for material model iterations.
<code>absolute_tolerance</code>	Absolute convergence tolerance for material model iterations.
<code>max_its</code>	Maximum number of material model convergence iterations.
<code>output_iteration_info</code>	Whether to output material model convergence information.
<code>stress_free_temperature</code>	The stress-free temperature. If not specified, the initial temperature is used.
<code>matpro_youngs_modulus</code>	Set to true to use correlations for Young's modulus from MATPRO [8].
<code>matpro_poissons_ratio</code>	Set to true to use correlations for Poisson's modulus from MATPRO [8].
<code>matpro_thermal_expansion</code>	Set to true to use correlations for coefficient of thermal expansion from MATPRO [8].
<code>burnup</code>	Name of burnup variable. Only required if using MATPRO correlations. Typically <code>burnup</code> .

16.2.6 CreepUPuZr

CreepUPuZr is used to model the thermal and irradiation creep behavior of U-Pu-Zr fast reactor fuel. If porosity and porosity_material are both defined an error will result. The user has the choice of not supplying any porosity, supplying a variable for porosity or couple to a material that calculates the porosity.

```
[./creepupuzr]
  type = CreepUPuZr
  disp_x = <string>
  disp_y = <string>
  disp_z = <string>
  disp_r = <string>
  temp = <string>
  porosity = <string>
  porosity_material = <bool> (false)
  fission_rate = <string>
  youngs_modulus = <real>
  poissons_ratio = <real>
  thermal_expansion = <real> (0)
  stress_free_temperature = <real>
[../]
```

type	CreepUPuZr
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.
disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
porosity	Variable name corresponding to the porosity. Typically porosity.
porosity_material	A flag indicating whether porosity is being calculated by a material property (e.g., VSwellingUPuZr). Optional.
fission_rate	Variable name corresponding to the fast neutron flux. Typically fission_rate.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.
thermal_expansion	Coefficient of thermal expansion.

stress_free_temperature The stress-free temperature. If not specified, the initial temperature is used.

16.2.7 Elastic

The Elastic model is a simple hypo-elastic model.

```
[./elastic]
type = Elastic
disp_x = <string>
disp_y = <string>
disp_z = <string>
disp_r = <string>
temp = <string>
youngs_modulus = <real>
poissons_ratio = <real>
thermal_expansion = <real> (0)
stress_free_temperature = <real>
[../]
```

type	Elastic
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.
disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.
thermal_expansion	Coefficient of thermal expansion.
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.

16.2.8 FailureCladding

FailureCladding is the model for Zircaloy-4 cladding failure due to burst during a LOCA accident.

```
[./failurecladding]
type = FailureCladding
```

```

boundary = <string list>
criterion = <integer> (2)
hoop_stress = <string>
eff_strain_rate_creep = <string>
eff_strain_rate_plast = <string>
temperature = temperature
fract_beta_phase = <string>
fract_oxygen_gain = <string>
[../]

```

type	FailureCladding
boundary	Required. Waterside cladding boundary. The model in the current version is applied to the boundary because it is coupled to the waterside oxidation model (Section 16.2.13).
criterion	Choice of the failure criterion. One of 0 (overstress), 1 (plastic instability) or 2 (combined overstress and plastic instability). criterion = 2 is recommended.
hoop_stress	Name of hoop stress auxiliary variable. For evaluating overstress.
eff_strain_rate_creep	Name of the auxiliary variable for the effective strain rate due to creep. For evaluating plastic instability.
eff_strain_rate_plast	Name of the auxiliary variable for the effective strain rate due to plasticity. For evaluating plastic instability.
temperature	Name of temperature variable. For evaluating overstress.
fract_beta_phase	Name of the auxiliary variable for the volume fraction of Zr β phase, calculated by the model ZrPhase (Section 16.2.20).
fract_oxygen_gain	Name of the auxiliary variable for the gained weight fraction of oxygen in the cladding, calculated by the model Oxidation-Cladding (Section 16.2.13).

16.2.9 IrradiationGrowthZr4

The IrradiationGrowthZr4 model incorporates anisotropic volumetric swelling to track axial elongation in Zr4 cladding.

```

[./irradiationgrowthzr4]
type = IrradiationGrowthZr4
fast_neutron_fluence = <string>
Ag = <real> (3e-20)
ng = <real> (0.794)
[../]

```

type	IrradiationGrowthZr4
------	----------------------

fast_neutron_fluence	Name of fast neutron fluence variable. Typically fast_neutron_fluence.
Ag	Material constant that depends on the cladding metalurgical state.
ng	Material constant that depends on the cladding metalurgical state.

16.2.10 MechFeCrAl

The MechFeCrAl model computes the elastic moduli, coefficient of thermal expansion, and thermal creep of a variety of FeCrAl alloys being considered for accident tolerant cladding.

```
[./mechFeCrAl]
  type = MechFeCrAl
  block = <string list>
  disp_x = <string>
  disp_y = <string>
  disp_z = <string>
  disp_r = <string>
  temp = <string>
  fast_neutron_flux = <string>
  youngs_modulus = <real>
  poissons_ratio = <real>
  material = <string>
  scale_factor_A = <real> (1.0)
  scale_factor_Q = <real> (1.0)
  scale_factor_n = <real> (1.0)
  scale_factor_alpha = <real> (1.0)
  scale_factor_cte = <real> (1.0)
  scale_factor_youngs = <real> (1.0)
  scale_factor_nu = <real> (1.0)
  model_thermal_expansion = <bool> (true)
  model_elastic_modulus = <bool> (false)
  model_thermal_creep = <bool> (true)
  model_irradiation_creep = <bool> (true)
  stress_free_temperature = <real>
[../]
```

type	MechFeCrAl.
block	The list of blocks this material applies to.
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.
disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.

disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
fast_neutron_flux	Name of the fast flux variable. Typically fast_neutron_flux.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.
material	Name of chosen FeCrAl alloy. Choices are MA956, PM2000, APMT, FECRALLOY.
scale_factor_A	Scale factor to be applied to the creep prefactor.
scale_factor_Q	Scale factor to be applied to the creep activation energy.
scale_factor_n	Scale factor to be applied to the creep stress exponent.
scale_factor_alpha	Scale factor to be applied to the temperature coefficient.
scale_factor_cte	Scale factor to be applied to the thermal expansion coefficient.
scale_factor_youngs	Scale factor to be applied to the Young's modulus.
scale_factor_nu	Scale factor to be applied to the Poisson's ratio.
model_thermal_expansion	Whether to calculate the thermal expansion coefficient as a function of temperature.
model_elastic_modulus	Whether to calculate temperature dependent elastic moduli.
model_thermal_creep	Whether or not to model thermal creep.
model_irradiation_creep	Whether or not to model irradiation creep.
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.

16.2.11 MechMaterial

The MechMaterial model computes the elastic moduli and thermal expansion a variety of materials. The MechMaterial is used to describe a variety of materials that have the same form in the input file. The choices are MechAlloy33, MechHT9, MechMo, and MechSS316. These materials are typically used as cladding materials. Examples of their use can be found in /bison/tests/HT9 and /bison/tests/mechTests/.

```
[./mechMaterial]
  type = Mech<string>
  block = <string list>
  disp_x = <string>
  disp_y = <string>
  disp_z = <string>
  disp_r = <string>
  temp = <string>
  youngs_modulus = <real>
```

```
poissons_ratio = <real>
[../]
```

type	Mech<string>. Where <string> represents the particular material to be used (e.g. HT9).
block	The list of blocks this material applies to.
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.
disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.
temp	Name of temperature variable. Typically temp.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.

16.2.12 MechZry

The MechZry model includes the options to model primary, thermal, and irradiation-induced creep. Modeling of creep under LOCA conditions is available. Also, it is possible to turn on irradiation growth. If irradiation growth is turned on, do not include the IrradiationGrowthZr4 model. Finally, an accuracy-controlling time step criterion is implemented, which can be applied through the MaterialTimeStep postprocessor (Section 18.6).

```
[../mechzry]
type = MechZry
fast_neutron_flux = <string>
fast_neutron_fluence = <string>
initial_fast_fluence = <real> (0.0)
cold_work_factor = <real> (0.01)
constitutive_model = <string>
oxygen_concentration = <real> (0.0)
relative_tolerance = <real> (1e-4)
absolute_tolerance = <real> (1e-20)
max_its = <integer> (10)
output_iteration_info = <bool> (false)
output_iteration_info_on_error = <bool> (false)
model_irradiation_creep = <bool> (true)
model_primary_creep = <bool> (true)
model_thermal_creep = <bool> (true)
model_thermal_creep_loca = <bool> (false)
model_irradiation_growth = <bool> (true)
growth_direction = <integer>
model_thermal_expansion = <bool> (true)
```

```

model_elastic_modulus = <bool> (false)
stress_free_temperature = <real>
material_type = <string>(SRA) or <integer>(0)
temp_standard_creep_end = <real> (700.)
temp_loca_creep_begin = <real> (900.)
max_creep_increment = <real> (1.e-03)
creeprate_scalef = <real> (1.)
[../]

```

type	MechZry
fast_neutron_flux	Variable name corresponding to the fast neutron flux. Typically <code>fast_neutron_flux</code> .
fast_neutron_fluence	Name of fast neutron fluence variable. Typically <code>fast_neutron_fluence</code> .
initial_fast_fluence	The initial fast neutron fluence.
constitutive_model	Name of constitutive model.
cold_work_factor	Cold work factor.
oxygen_concentration	Oxygen concentration in ppm.
relative_tolerance	Relative convergence tolerance for material model iterations.
absolute_tolerance	Absolute convergence tolerance for material model iterations.
max_its	Maximum number of material model convergence iterations.
output_iteration_info	Whether to output material model convergence information.
output_iteration_info_on_error	Whether to output material model convergence information if an error occurs.
model_irradiation_creep	Whether to model irradiation-induced creep.
model_primary_creep	Whether to model primary creep.
model_thermal_creep	Whether to model steady state thermal creep.
model_thermal_creep_loca	Whether to model thermal creep considering a specific correlation at LOCA temperatures.
model_irradiation_growth	Whether to model irradiation growth.
growth_direction	The direction in which irradiation growth is applied. Typically 1 (axial direction).
model_thermal_expansion	Whether to use MATPRO model for thermal expansion.
model_elastic_modulus	Whether to calculate temperature-dependent elastic moduli.

stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.
material_type	Cladding material type. SRA(or 0), RXA(or 1), or PRXA(or 2).
temp_standard_creep_end	The upper limit of temperature where the standard thermal creep model no longer applies.
temp_loca_creep_begin	The lower limit of temperature where the loca thermal creep model begins to apply.
max_creep_increment	The maximum increment of effective creep strain allowed by the time step control.
creep_rate_scalef	Scale factor applied to the creep rate (for sensitivity studies).

16.2.12.1 CombinedCreepPlasticity

The CombinedCreepPlasticity model is used when it is specified as the constitutive_model in MechZry. CombinedCreepPlasticity models the deformation under both creep and instantaneous plasticity. Submodels need to be specified in the input to model creep and instantaneous plasticity of Zry cladding.

```
[./CombinedCreepPlasticity]
  type = CombinedCreepPlasticity
  relative_tolerance = <real> (1e-5)
  absolute_tolerance = <real> (1e-5)
  max_its = <integer> (30)
  output_iteration_info = <bool> (false)
  output_iteration_info_on_error = <bool> (false)
  submodels = <string>
[../]
```

type	CombinedCreepPlasticity
relative_tolerance	Relative convergence tolerance for combined submodel iterations.
absolute_tolerance	Absolute convergence tolerance for combined submodel iterations.
max_its	Maximum number of submodel convergence iterations.
output_iteration_info	Whether to output submodel convergence information.
output_iteration_info_on_error	Whether to output submodel convergence information if an error occurs.
submodels	Name of submodels used for combined creep and plasticity.

16.2.12.2 CreepZryModel

The CreepZryModel model is the default constitutive model used in MechZry. Therefore, the interface is similar to the MechZry except for the options and parameters to model elastic modulus, thermal expansion, and irradiation growth. This model is used as a separate block in the input file when it is specified as one of the submodels in CombinedCreepPlasticity model.

```
[./CreepZryModel]
  type = CreepZryModel
  fast_neutron_flux = <string>
  fast_neutron_fluence = <string>
  initial_fast_fluence = <real>
  cold_work_factor = <real> (0.01)
  oxygen_concentration = <real> (0.0)
  relative_tolerance = <real> (1e-5)
  absolute_tolerance = <real> (1e-20)
  max_its = <integer> (30)
  output_iteration_info = <bool> (false)
  output_iteration_info_on_error = <bool> (false)
  model_irradiation_creep = <bool> (true)
  model_primary_creep = <bool> (true)
  model_thermal_creep = <bool> (true)
  model_thermal_creep_loca = <bool> (false)
  material_type = <string>(SRA) or <integer>(0)
  temp_standard_creep_end = <real> (700.)
  temp_loca_creep_begin = <real> (900.)
  max_creep_increment = <real> (1.e-03)
  creeprate_scalef = <real> (1.)
[../]
```

type	CreepZryModel
fast_neutron_flux	Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.
fast_neutron_fluence	Name of fast neutron fluence variable. Typically fast_neutron_fluence.
initial_fast_fluence	The initial fast neutron fluence.
cold_work_factor	Cold work factor.
oxygen_concentration	Oxygen concentration in ppm.
relative_tolerance	Relative convergence tolerance for material model iterations.
absolute_tolerance	Absolute convergence tolerance for material model iterations.
max_its	Maximum number of material model convergence iterations.
output_iteration_info	Whether to output material model convergence information.

<code>output_iteration_info_on_error</code>	Whether to output material model convergence information if an error occurs.
<code>model_irradiation_creep</code>	Whether to model irradiation-induced creep.
<code>model_primary_creep</code>	Whether to model primary creep.
<code>model_thermal_creep</code>	Whether to model steady state thermal creep.
<code>model_thermal_creep_loca</code>	Whether to model thermal creep considering a specific correlation at LOCA temperatures.
<code>material_type</code>	Cladding material type. SRA(or 0), RXA(or 1), or PRXA(or 2).
<code>temp_standard_creep_end</code>	The upper limit of temperature where the standard thermal creep model no longer applies.
<code>temp_loca_creep_begin</code>	The lower limit of temperature where the loca thermal creep model begins to apply.
<code>max_creep_increment</code>	The maximum increment of effective creep strain allowed by the time step control.
<code>creep_rate_scalef</code>	Scale factor applied to the creep rate (for sensitivity studies).

16.2.12.3 IsotropicPlasticity

The `IsotropicPlasticity` model is a model used to model the instantaneous plasticity of Zry cladding. It is used as one of the submodels in `CombinedCreepPlasticity` model.

```
[./IsotropicPlasticity]
  type = IsotropicPlasticity
  relative_tolerance = <real> (1e-5)
  absolute_tolerance = <real> (1e-20)
  max_its = <integer> (30)
  output_iteration_info = <bool> (false)
  output_iteration_info_on_error = <bool> (false)
  hardening_constant = <real>
  hardening_function = <string>
  yield_stress = <real>
[../]
```

<code>type</code>	<code>IsotropicPlasticity</code>
<code>relative_tolerance</code>	Relative convergence tolerance for sub-newton iterations.
<code>absolute_tolerance</code>	Absolute convergence tolerance for sub-newton iterations.
<code>max_its</code>	Maximum number of sub-newton convergence iterations.

output_iteration_info	Whether to output sub-newton convergence information.
output_iteration_info_on_error	Whether to output material model convergence information if an error occurs.
hardening_constant	Input hardening slope.
hardening_function	True stress as a function of plastic strain.
yield_stress	Input initial yeild stress.

16.2.13 OxidationCladding

The OxidationCladding model incorporates correlations for Zircaloy cladding oxidation through metal-water reactions. Described processes include outer oxide scale thickness growth and oxygen mass gain. The model is to be applied to the cladding waterside boundary.

```
[./oxidationcladding]
  type = OxidationCladding
  boundary = <string list>
  clad_inner_radius = <real>
  clad_outer_radius = <real>
  normtemp_model = 0
  hightemp_model = <integer> (0)
  temperature = <string>
  fast_neutron_flux = <string>
  use_coolant_channel = <bool> (false)
  oxygen_wtfract_initial = <real> (0.0012)
  oxidation_scalef = <real> (1.)
[../]
```

type	OxidationCladding
boundary	Required. Waterside cladding boundary.
clad_inner_radius	Required. Inner cladding radius (m).
clad_outer_radius	Required. Outer cladding radius (m).
normtemp_model	Selection of the normal operating temperatures correlation. Only 0 (EPRI/KWU/C-E) is considered at this time.
hightemp_model	Selection of the high temperatures correlation. One of 0 (Leistikov) or 1 (Cathcart-Pawel). In both cases, the model uses the Prater-Courtright correlation above 1900 K.
temp	Required. Name of temperature variable. Typically temp.
fast_neutron_flux	Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.
use_coolant_channel	If true, the model will adjust the surface temperature based on the coolant channel model.
oxygen_wtfract_initial	As-fabricated oxygen weight fraction in cladding.

oxidation_scalef Scale factor applied to the oxide scale thickness (for sensitivity studies).

16.2.14 RelocationUO2

The RelocationUO2 model accounts for cracking and relocation of fuel pellet fragments in the radial direction. This model is necessary for accurate modeling of LWR fuel. Only one of *q* and *q_variable* may be given.

```
[./relocationuo2]
  type = RelocationUO2
  burnup_function = <string>
  burnup = <string>
  fuel_pin_geometry = <string>
  diameter = <real>
  q = <string>
  q_variable = <string>
  gap = <real>
  burnup_relocation_stop = <real>
  relocation_activation1 = <real> (19685.039)
  relocation_activation2 = <real> (45931.759)
  relocation_activation3 = <real> (32808.399)
  axial_axis = <0, 1, or 2 for x, y, or z>
  model = <ESCORE_modified, ESCORE, or GAPCON> (ESCORE_modified)
[../]
```

type	RelocationUO2
burnup_function	Name of the Burnup sub-block, if any (typically burnup). May not be used with the burnup line command. Use of burnup_function is preferred.
burnup	Name of burnup variable. Typically burnup.
fuel_pin_geometry	Name of the FuelPinGeometry object (see 23.1).
diameter	Required if fuel_pin_geometry is not specified. As fabricated cold diameter of pellet in meters.
q	Function describing linear heat rate in pellet in W/m.
q_variable	Variable holding linear heat rate in pellet in W/m.
gap	Required if fuel_pin_geometry is not specified. As fabricated cold diametral gap in m.
burnup_relocation_stop	Burnup at which relocation strain stops in FIMA.
relocation_activation1	First activation linear power in W/m. The linear power at which relocation turns on.
relocation_activation2	Second activation linear power in W/m. The linear power at which relocation transitions from the initial regime to the secondary regime.

relocation_activation3	Third activation linear power in W/m. The linear power offset in the secondary regime.
axial_axis	Coordinate axis of the axial direction of the fuel stack.
model	Which relocation correlation to use.

16.2.15 ThermalIrradiationCreepZr4

The ThermalIrradiationCreepZr4 is used for Zr4 cladding in LWR simulations. It includes fits for the temperature, irradiation, and stress effects on cladding creep.

```
[./thermalirradiationcreepzr4]
type = ThermalIrradiationCreepZr4
disp_x = <string>
disp_y = <string>
disp_z = <string>
disp_r = <string>
temp = <string>
a_coeff = <real> (3.14e24)
n_exponent = <real> (5)
activation_energy = <real> (2.7e5)
gas_constant = <real> (8.3143)
fast_neutron_flux = <string>
c0_coef = <real> (9.881e-28)
c1_coef = <real> (0.85)
c2_coef = <real> (1)
youngs_modulus = <real>
poissons_ratio = <real>
thermal_expansion = <real> (0)
relative_tolerance = <real> (1e-4)
absolute_tolerance = <real> (1e-20)
max_its = <integer> (10)
output_iteration_info = <true or false> (false)
stress_free_temperature = <real>
[../]
```

type	ThermalIrradiationCreepZr4
disp_x	Variable name for displacement variable in x direction. Typically disp_x.
disp_y	Variable name for displacement variable in y direction. Typically disp_y.
disp_z	Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.
disp_r	Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.

temp	Name of temperature variable. Typically temp.
a_coef	The leading coefficient in the thermal creep term.
n_exponent	The exponent in the thermal creep term.
activation_energy	The activation energy.
gas_constant	The universal gas constant.
fast_neutron_flux	Variable name corresponding to the fast neutron flux. Typically fast_neutron_flux.
c0_coef	The leading coefficient in the irradiation creep term.
c1_exponent	The exponent on the irradiation creep fast neutron flux term.
c2_exponent	The exponent on the irradiation creep stress term.
youngs_modulus	Young's modulus.
poissons_ratio	Poisson's ratio.
thermal_expansion	Coefficient of thermal expansion.
relative_tolerance	Relative convergence tolerance for material model iterations.
absolute_tolerance	Absolute convergence tolerance for material model iterations.
max_its	Maximum number of material model convergence iterations.
output_iteration_info	Whether to output material model convergence information.
stress_free_temperature	The stress-free temperature. If not specified, the initial temperature is used.
burnup	Name of burnup variable. Typically burnup.

16.2.16 PyCIrradiationStrain

The PyCIrradiationStrain model tracks the irradiation-induced strain in pyrolytic carbon. The strain is isotropic for the buffer type and differs in the radial and tangential directions for the dense type.

```
[./pycirradiationstrain]
  type = PyCIrradiationStrain
  fluence = <string>
  pyc_type = <string> (buffer)
[../]
```

type	PyCIrradiationrStrain
fluence	Required. Variable name corresponding to the fast neutron fluence. Typically fast_neutron_fluence.
pyc_type	One of buffer or dense.

16.2.17 VSwellingFeCrAl

The VSwellingFeCrAl model computes a volumetric strain to account for irradiation induced swelling of FeCrAl alloys used for cladding.

```
[./vswelling_fecral]
  type = VSwellingFeCrAl
  fast_neutron_fluence = <string>
  swelling_scalef = <real> (1.0)
[../]
```

type	VSwellingFeCrAl
fast_neutron_fluence	The name of the variable for the fast neutron fluence.
swelling_scalef	A scaling factor to be applied to the swelling creep strain.

16.2.18 VSwellingUO2

The VSwellingUO2 model computes a volumetric strain to account for solid and gaseous swelling and for densification. VSwellingUO2 also computes porosity (fabrication_porosity, gaseous_porosity, and sintering_porosity).

```
[./vswellinguo2]
  type = VSwellingUO2
  temp = <string>
  burnup_function = <string>
  burnup = <string>
  density = <real>
  total_densification = <real> (0.01)
  complete_burnup = <real> (5)
  initial_porosity = <real> (0.05)
  save_solid_swell = <bool> (false)
  save_densification = <bool> (false)
  gas_swelling_type = <string> (SIFGRS)
[../]
```

type	VSwellingUO2
temp	Name of temperature variable. Typically temp.
burnup_function	Name of the Burnup sub-block, if any (typically burnup). May not be used with the burnup line command. Use of burnup_function is preferred.
burnup	Name of burnup variable. Typically burnup.
density	Required. Initial fuel density.
total_densification	The densification that will occur given as a fraction of theoretical density.
complete_burnup	The burnup at which densification is complete (MWd/kgU).

<code>initial_porosity</code>	The initial fuel porosity.
<code>save_solid_swell</code>	Whether to save the solid swelling as a material property (<code>solid_swell</code>).
<code>save_densification</code>	Whether to save the densification as a material property (<code>densification</code>).
<code>gas_swelling_type</code>	Either <code>SIFGRS</code> to use the gas swelling computed by the Sifgrs model or <code>MATPRO</code> to use MATPRO's empirical model. IMPORTANT: if using <code>SIFGRS</code> , the following line must be placed in the block defining the solid mechanics material model for the fuel (e.g., <code>CreepUO2</code> or <code>Elastic</code>) so that the models run in the correct order: " <code>dep_matl_props = deltav_v0_bd</code> "

Note that the total swelling will be stored as a material property (named `total_swell`) if both `save_solid_swell` and `save_densification` are true. Solid swelling is saved as `solid_swell`, and densification is saved as `densification`. The total swelling includes solid swelling, densification, and gaseous swelling. Gaseous swelling is always stored as a material property (named `gas_swell`).

16.2.19 VSwellingUPuZr

The `VSwellingUPuZr` model computes a volumetric strain to account for solid and gaseous swelling for U-Pu-Zr metal fuel systems.

```
[./vswelling_upuzr]
  type = VSwellingUPuZr
  temp = <string>
  fission_rate = <string>
  hydrostatic_stress = <string>
  fabrication_porosity = <real> (0.0)
[../]
```

<code>type</code>	<code>VSwellingUPuZr</code>
<code>temp</code>	Name of temperature variable. Typically <code>temp</code> .
<code>fission_rate</code>	Name of fission rate variable. Typically <code>fission_rate</code> .
<code>hydrostatic_stress</code>	Name of hydrostatic stress variable. Typically <code>hydrostatic_stress</code> .
<code>fabrication_porosity</code>	The as-fabricated porosity

Note that solid swelling and gaseous swelling are always saved as a material property, named `solid_swell` and `gas_swell`, respectively. Also, porosity (as-fabricated + gas swelling porosity) is available as a material property.

16.2.20 ZrPhase

The ZrPhase model computes the volume fraction of β phase for Zr-based cladding materials as a function of temperature and time.

```
[./zrphase]
  type = ZrPhase
  block = <string list>
  temperature = <string>
  numerical_method = <integer>
[../]
```

type	ZrPhase
block	List of blocks this material model applies to.
temperature	Required. Name of temperature variable. Typically temp.
numerical_method	Choice of numerical method to solve the differential equation for the phase transformation rate. One of 1 (implicit Euler method) or 2 (second order Adams-Moulton method - AM2).

16.3 Mass Diffusion Models

This material computes a two-term Arrhenius diffusion coefficient of the form

$$d = d_1 \exp\left(\frac{-q_1}{RT}\right) + d_2 \exp\left(\frac{-q_2}{RT}\right). \quad (16.2)$$

```
[./arrheniusdiffusioncoef]
  type = ArrheniusDiffusionCoef
  d1 = <real> (5.6e-8)
  d1_function = <string>
  d1_function_variable = <string>
  d2 = <real> (5.2e-4)
  q1 = <real> (2.09e5)
  q2 = <real> (3.62e5)
  gas_constant = <real> (8.3143)
  temp = <string>
[../]
```

type	ArrheniusDiffusionCoef
d1	First coefficient (m ² /2).
d1_function	Function to be multiplied by d1.
d1_function_variable	Variable to be used when evaluating d1_function. If not given, time will be used.
d2	Second coefficient (m ² /2).

q1	First activation energy (J/mol).
q2	Second activation energy (J/mol).
gas_constant	Universal gas constant (J/mol/K).
temp	Name of temperature variable. Typically temp.

16.4 Other Models

16.4.1 Arrhenius Material Property

ArrheniusMaterialProperty is used to declare an arbitrary material property D that has the form $D = Ae^{-Q/RT}$, where A is the frequency factor, Q is the activation energy, R is the gas constant, and T is the temperature.

```
[./some_property]
  type = ArrheniusMaterialProperty
  frequency_factor = <real>
  activation_energy = <real>
  gas_constant = <real> (8.314)
  temp = <variable>
  property_name = <string>
[../]
```

type	ArrheniusMaterialProperty
frequency_factor	The coefficient in front of the exponential.
activation_energy	The activation energy.
gas_constant	The universal gas constant.
temp	Coupled temperature variable.
property_name	The name for this property.

16.4.2 Density

The Density model creates a material property named density. If coupled to displacement variables, the model adjusts density based on deformation.

```
[./density]
  type = Density
  disp_x = <string>
  disp_y = <string>
  disp_z = <string>
  disp_r = <string>
  density = <real>
[../]
```

type	Density
------	---------

disp_x Variable name for displacement variable in x direction. Typically disp_x.

disp_y Variable name for displacement variable in y direction. Typically disp_y.

disp_z Variable name for displacement variable in z direction. Typically disp_z for 3D and disp_y for axisymmetric models.

disp_r Variable name for displacement variable in radial direction for axisymmetric or spherically symmetric cases. Typically disp_x.

density **Required.** Density.

17 Fission Gas Models

Fission gas production and release modeling plays a vital role in fuel performance analysis. Fission gas affects swelling, porosity, thermal conductivity, gap conductivity, and rod internal pressure. The `Sifgrs` model is recommended.

17.1 Sifgrs

`Sifgrs` is the recommended fission gas model. It computes both fission gas release and fuel gaseous swelling.

```
[./sifgrs]
type = Sifgrs
initial_porosity = <real> (0.05)
grain_radius_const = <real> (5.e-06)
hydrostatic_stress_const = <real> (0.)
saturation_coverage = <real> (0.5)
ath_model = <bool> (false)
gbs_model = <bool> (false)
hbs_model = <bool> (false)
grain_radius = <string>
temp = <string>
fission_rate = <string>
burnup = <string>
burnup_function = <string>
hydrostatic_stress = <string>
pellet_id = <string>
pellet_brittle_zone = <string>
diff_coeff_option = <integer> (3)
res_param_option = <integer> (0)
transient_option = <integer> (0)
rod_ave_lin_power = <string>
axial_power_profile = <string>
temperature_scalef = <real> (1.)
grainradius_scalef = <real> (1.)
igdiffcoeff_scalef = <real> (1.)
resolutionp_scalef = <real> (1.)
gbdiffcoeff_scalef = <real> (1.)
[../]
```

<code>type</code>	<code>Sifgrs</code>
<code>initial_porosity</code>	Initial fuel porosity (/).

<code>grain_radius_const</code>	A constant value for fuel grain radius (m). Ignored if <code>grain_radius</code> is given.
<code>hydrostatic_stress_const</code>	A constant value for hydrostatic stress (Pa). Ignored if <code>hydrostatic_stress</code> is given.
<code>saturation_coverage</code>	Initial value of fractional grain boundary bubble coverage at saturation (/).
<code>ath_model</code>	Whether to consider athermal (recoil and knockout) gas release.
<code>gbs_model</code>	Whether to consider the grain boundary sweeping effect.
<code>hbs_model</code>	Whether to consider intra-granular gas depletion in the high burnup structure (HBS).
<code>grain_radius</code>	Name of the auxiliary variable for grain radius, calculated by <code>GrainRadiusAux</code> (Section 12.3.5). Typically <code>grain_radius</code> .
<code>temp</code>	Variable name for temperature variable. Typically <code>temp</code> .
<code>fission_rate</code>	Variable name corresponding to the fission rate. Typically <code>fission_rate</code> .
<code>burnup</code>	Name of burnup variable. Typically <code>burnup</code> .
<code>burnup_function</code>	Name of the <code>Burnup</code> sub-block, if any (typically <code>burnup</code>). May not be used with <code>fission_rate</code> . Use of <code>burnup_function</code> is preferred.
<code>hydrostatic_stress</code>	Variable name for hydrostatic stress. Typically <code>hydrostatic_stress</code> .
<code>pellet_id</code>	Name of the auxiliary variable for pellet id. Typically <code>pellet_id</code> . Used if <code>ath_model = true</code> .
<code>pellet_brittle_zone</code>	The name of the <code>UserObject</code> that computes the width of the brittle zone in the fuel pellet. Used if <code>ath_model = true</code> .
<code>diff_coeff_option</code>	Choice of the intra-granular diffusion coefficient. One of 0 (Turnbull et al. [9] with purely irradiation-dependent term not considered), 1 (Andersson et al. [10]), 2 (Turnbull et al. [11]), or 3 (Turnbull et al. [11] with purely irradiation-dependent term not considered).
<code>res_param_option</code>	Choice of the intra-granular resolution parameter. One of 0 (heterogeneous model [12]) or 1 (compromise between the heterogeneous and the homogeneous models, see [13] – for sensitivity studies).
<code>transient_option</code>	To consider the burst release effect during transients, set equal to 2.
<code>rod_ave_lin_pow</code>	Function describing rod averaged linear power.
<code>axial_power_profile</code>	Function describing axial power profile.
<code>temperature_scalef</code>	Scale factor applied to temperature (for sensitivity studies).

grainradius_scalef	Scale factor applied to grain radius (for sensitivity studies).
igdiffcoeff_scalef	Scale factor applied to intra-granular diffusion coefficient (for sensitivity studies).
resolutionp_scalef	Scale factor applied to intra-granular resolution parameter (for sensitivity studies).
gbdiffcoeff_scalef	Scale factor applied to grain-boundary diffusion coefficient (for sensitivity studies).

17.2 ForMas

The ForMas model is maintained but not actively developed. The Sifgrs model is recommended.

```
[./formas]
type = ForMas
grain_radius = <real> (10e-6)
resolution_rate = <real> (1e-7)
resolution_depth = <real> (1e-8)
bubble_radius = <real> (5e-7)
bubble_shape_factor = <real> (0.287)
surface_tension = <real> (0.626)
fractional_coverage = <real> (0.5)
external_pressure = <real> (10e6)
plenum_pressure = <string>
external_pressure_function = <string>
release_fraction = <real> (0)
fractional_yield = <real> (0.3017)
calibration_factor = <real> (1)
[../]
```

type	ForMas
grain_radius	Initial fuel grain radius.
resolution_rate	Resolution rate from intergranular bubbles (1/s).
resolution_depth	Resolution layer depth.
bubble_radius	Grain boundary bubble radius.
bubble_shape_factor	Non-spherical bubble shape factor.
surface_tension	Bubble surface tension (J/m ²).
fractional_coverage	Fractional coverage of grain boundary at saturation.
external_pressure	Constant external hydrostatic pressure.
plenum_pressure	The name of the plenum pressure Postprocessor.
external_pressure_function	Function describing the external pressure.

release_fraction	Fraction of boundary and resolved gas released at saturation.
fractional_yield	Fractional yield of fission gas atoms per fission.
calibration_factor	Calibration factor to be multiplied by gas saturation density.

17.3 FgrUPuZr

FgrUPuZr is a fission gas release model for UPuZr metal fuel.

```
[./upuzr_fission_gas_release]
  type = FgrUPuZr
  fission_rate = <string>
  fractional_yield = <real> (0.3017)
[../]
```

type	FgrUPuZr
fission_rate	Coupled Fission Rate
fractional_yield	Fractional yield of fission gas atoms per fission.

18 Postprocessors

MOOSE `Postprocessors` compute a single scalar value at each timestep. These can be minimums, maximums, averages, volumes, or any other scalar quantity. One example of the use of `Postprocessors` in BISON is computing the gas volume of an LWR rod. The gas volume changes timestep to timestep, but since it is a single scalar quantity, a `Postprocessor` computes this value.

```
[Postprocessors]
  [./name]
    type = <postprocessor type>
    block = <string list>
    boundary = <string list>
    outputs = <string>
    ...
  [../]
[]
```

<code>type</code>	Type of postprocessor
<code>block</code>	List of blocks. Either block numbers or names.
<code>boundary</code>	List of boundaries (side sets). Either boundary numbers or names.
<code>outputs</code>	Vector of output names where you would like to restrict the output of variable(s) associated with the postprocessor.

Most `Postprocessors` act on either boundaries or blocks. If no block or boundary is specified, the `Postprocessor` will act on the entire model. There are a few `Postprocessors` that act on specific nodes or elements within the finite element mesh.

18.1 DecayHeatFunction

`DecayHeatFunction` computes the value of the decay heat function. The value is zero prior to the specified `time_at_shutdown`. This postprocessor is typically used for Loss of Coolant Accident simulations.

```
[./decayheatfunction]
  type = DecayHeatFunction
  energy_per_fission = <real> (3.28451e-11)
  neutron_capture_factor = <real> (1)
  time_at_shutdown = <real> (1e10)
[../]
```

type	DecayHeatFunction
energy_per_fission	The energy released per fission in J/fission.
neutron_capture_factor	The neutron capture factor used to account for the effect of neutron capture in fission products.
time_at_shutdown	The time the reactor is shutdown and decay heat begins to take effect.

18.2 ElementIntegralPower

ElementIntegralPower computes the power in the supplied block given the fission rate variable and energy per fission.

```
[./elementintegralpower]
  type = ElementIntegralPower
  burnup_function = <string>
  fission_rate = <string>
  energy_per_fission = <real> (3.28451e-11)
  variable = <string>
[../]
```

type	ElementIntegralPower
burnup_function	Name of the Burnup sub-block, if any (typically burnup). May not be used with fission_rate. Use of burnup_function is preferred.
fission_rate	Variable name corresponding to the fission rate. Typically fission_rate.
energy_per_fission	The energy released per fission in J/fission.
variable	The variable name this Postprocessor applies to. Typically temp.

18.3 ElementalVariableValue

In some cases it may be of interest to output an elemental variable value (e.g., stress) at a particular location in the model. This is accomplished by using the ElementalVariableValue postprocessor.

```
[./elementalvariablevalue]
  type = ElementalVariableValue
  elementid = <string>
  variable = <string>
[../]
```

type	ElementalVariableValue
elementid	Required. The global element id from the mesh to which this postprocessor is to be applied.

variable **Required.** The variable whose value is output to this postprocessor for the given element.

18.4 Fission Gas Postprocessors

When using the Sifgrs fission gas release model there are four postprocessors that are used to report the fission gas that is produced in moles (ElementIntegralFisGasGeneratedSifgrs), fission gas within the grains (ElementIntegralFisGasGrainSifgrs), fission gas on the grain boundary (ElementIntegralFisGasBoundarySifgrs), and the fission gas released to the plenum in moles (ElementIntegralFisGasReleasedSifgrs). The details of including these postprocessors in the input file is outlined below:

```
[./fis_gas_produced]
  type = ElementIntegralFisGasGeneratedSifgrs
  variable = <string>
  block = <string list>
[../]

[./fis_gas_grain]
  type = ElementIntegralFisGasGrainSifgrs
  variable = <string>
  block = <string list>
[../]

[./fis_gas_boundary]
  type = ElementIntegralFisGasBoundarySifgrs
  variable = <string>
  block = <string list>
[../]

[./fis_gas_released]
  type = ElementIntegralFisGasReleasedSifgrs
  variable = <string>
  block = <string list>
[../]
```

type The type of postprocessor

variable **Required.** The variable the postprocessor applies to. For these fission gas postprocessors the variable is typically temp.

block The blocks the postprocessor applies to. For nuclear fuel simulations fission gas calculations apply to the fuel/pellet block.

18.5 InternalVolume

InternalVolume computes the volume of an enclosed space. The entire boundary of the enclosed space must be represented by the given side set. If the given side set points outward, InternalVolume will report a negative volume.

```
[./internalvolume}  
  type = InternalVolume  
  scale_factor = <real> (1)  
  addition = <addition> (0)  
[../]
```

type InternalVolume
scale_factor Scale factor to be applied to the internal volume calculation.
addition Number to be added to internal volume calculation. This addition is not scaled.

18.6 MaterialTimeStep

MaterialTimeStep allows one to apply physics-based time step criteria implemented in material models. For this purpose, this postprocessor takes the overall minimum across the domain of the time steps provided by (one or more) material models. At this time, a creep rate based time step criterion is available in MechZry (Section 16.2.12). MaterialTimeStep will retrieve the time step length, which MechZry computes at each mesh point, and return the minimum. This time step can then be used by a time stepper such as PostprocessorDT. MaterialTimeStep can be extended to consider multiple material model time step criteria as they become available.

```
[./materialtimestep}  
  type = MaterialTimeStep  
  variable = <string>  
[../]
```

type MaterialTimeStep
variable **Required.** The variable whose value is output to this postprocessor.

18.7 NodalVariableValue

In order to obtain the value of a nodal variable at a particular location (i.e., temperature and displacement) a NodalVariableValue postprocessor is used. For example, this postprocessor is useful for obtaining the centerline temperature at the location of a thermocouple to compare against experimental data.

```
[./nodalvariablevalue]  
  type = NodalVariableValue
```

```
elementid = <string>
scale_factor = <real>
variable = <string>
[../]
```

type NodalVariableValue

nodeid **Required.** The global node id from the mesh to which this postprocessor is to be applied.

scale_factor A scalar value to be multiplied by the value of the variable.

variable **Required.** The variable whose value is output to this postprocessor for the given node.

18.8 NumNonlinearIterations

NumNonlinearIterations reports the number of nonlinear iterations in the just-completed solve.

```
[./numnonlineariters]
type = NumNonlinearIterations
[../]
```

type NumNonlinearIterations

18.9 PlotFunction

PlotFunction gives the value of the supplied function at the current time, optionally scaled with scale_factor.

```
[./plotfunction]
type = PlotFunction
function = <string>
scale_factor = <real> (1)
[../]
```

type PlotFunction

function **Required.** The function to evaluate.

scale_factor Scale factor to be applied to the function value.

18.10 SideAverageValue

SideAverageValue computes the area- or volume-weighted average of the named variable. It may be used, for example, to calculate the average temperature over a side set.

```
[./sideaveragevalue}  
  type = SideAverageValue  
  variable = <string>  
[../]
```

type SideAverageValue
variable **Required.** The variable this Postprocessor acts on.

18.11 SideFluxIntegral

SideFluxIntegral computes the integral of the flux over the given boundary.

```
[./sidefluxintegral]  
  type = SideFluxIntegral  
  variable = <string>  
  diffusivity = <string>  
[../]
```

type SideFluxIntegral
variable **Required.** Variable to be used in the flux calculation.
diffusivity **Required.** The diffusivity material property to be used in the calculation.

18.12 TimestepSize

TimestepSize reports the timestep size.

```
[./dt]  
  type = TimestepSize  
[../]
```

type TimestepSize

19 Solution Execution and Time Stepping

The `Executioner` block describes how the simulation will be executed. It includes commands to control the solver behavior and time stepping. Time stepping is controlled by a combination of commands in the `Executioner` block, and the `TimeStepper` block nested within the `Executioner` block.

```
[Executioner]
  type = <string>
  solve_type = <string>
  petsc_options = <string list>
  petsc_options_iname = <string list>
  petsc_options_value = <string list>
  line_search = <string>
  l_max_its = <integer>
  l_tol = <real>
  nl_max_its = <integer>
  nl_rel_tol = <real>
  nl_abs_tol = <real>
  start_time = <real>
  dt = <real>
  end_time = <real>
  num_steps = <integer>
  dtmax = <real>
  dtmin = <real>
  [TimeStepper]
    #TimeStepper commands
  [../]
```

<code>type</code>	Required. Several available. Typically <code>Transient</code> .
<code>solve_type</code>	One of <code>PJFNK</code> (preconditioned JFNK), <code>JFNK</code> (JFNK), <code>NEWTON</code> (Newton), or <code>SolveFD</code> (Jacobian computed by finite difference—serial only, slow).
<code>petsc_options</code>	PETSc flags.
<code>petsc_options_iname</code>	Names of PETSc name/value pairs.
<code>petsc_options_value</code>	Values of PETSc name/value pairs.
<code>line_search</code>	Line search type. Typically <code>none</code> .
<code>l_max_its</code>	Maximum number of linear iterations per solve.
<code>l_tol</code>	Linear solve tolerance.
<code>nl_max_its</code>	Maximum number of nonlinear iterations per solve.

<code>nl_reltol</code>	Nonlinear relative tolerance.
<code>nl_relabs</code>	Nonlinear absolute tolerance.
<code>start_time</code>	The start time of the analysis.
<code>end_time</code>	The end time of the analysis.
<code>num_steps</code>	The maximum number of time steps.
<code>dtmax</code>	The maximum allowed timestep size.
<code>dtmin</code>	The minimum allowed timestep size.

Several `Executioner` types exist, although the `Transient` type is typically the appropriate one to use for transient BISON analyses. For each type, specific options are available. To see the complete set of possibilities, follow the [Input Syntax](#) link on the BISON wiki page.

Similarly, many PETSc options exist. Please see the online PETSc documentation for details.

Given the many possibilities in the `Executioner` block, it may be helpful to review examples in the BISON tests, examples, and assessment directories.

19.1 Timestepping

The method used to calculate the size of the time steps taken by BISON is controlled by the `TimeStepper` block. There are a number of types of `TimeStepper` available. Three of the types most commonly used with BISON are described here. These permit the time step to be controlled directly by providing either a single fixed time step to take throughout the analysis, by providing the time step as a function of time, or by using adaptive timestepping algorithm can be used to modify the time step based on the difficulty of the iterative solution, as quantified by the numbers of linear and nonlinear iterations required to drive the residual below the tolerance required for convergence.

19.1.1 Direct Time Step Control with Constant Time Step

The `ConstantDT` type of `TimeStepper` simply takes a constant time step size throughout the analysis.

```
[TimeStepper]
  type = ConstantDT
  dt = <real>
[../]
```

`type` `ConstantDT`
`dt` **Required.** The initial timestep size.

`ConstantDT` begins the analysis taking the step specified by the user with the `dt` parameter. If the solver fails to obtain a converged solution for a given step, the executioner cuts back the step size and attempts to advance the time from the previous step using a smaller time step. The time step is cut back by multiplying the time step by 0.5.

If the solution with the cut-back time step is still un-successful, it is repeatedly cut back until a successful solution is obtained. The user can specify a minimum time step through the `dtmin` parameter in the `Executioner` block. If the time step must be cut back below the minimum size without obtaining a solution, BISON exits with an error. If the time step is cut back using `ConstantDT`, that cut-back step size will be used for the remainder of the the analysis.

19.1.2 Direct Time Step Control with Varying Time Step Size

If the `FunctionDT` type of `TimeStepper` is used, BISON takes time steps that vary over time according to a user-defined function.

```
[TimeStepper]
  type = FunctionDT
  time_t = <real list>
  time_dt = <real list>
[../]
```

- `type` `FunctionDT`
- `time_t` The abscissas of a piecewise linear function for timestep size.
- `time_dt` The ordinates of a piecewise linear function for timestep size.

The time step is controlled by a piecewise linear function defined using the `time_t` and `time_dt` parameters. A vector of time steps is provided using the `time_dt` parameter. An accompanying vector of corresponding times is specified using the `time_t` parameter. These two vectors are used to form a time step vs. time function. The time step for a given step is computed by linearly interpolating between the pairs of values provided in the vectors.

The same procedure that is used with `ConstantDT` is used to cut back the time step from the user-specified value if a failed solution occurs.

19.1.3 Adaptive Time Stepping

The `IterationAdaptiveDT` type of `TimeStepper` provides a means to adapt the time step size based on the difficulty of the solution.

```
[TimeStepper]
  type = IterationAdaptiveDT
  dt = <real>
  optimal_iterations = <integer>
  iteration_window = <integer> (0.2*optimal_iterations)
  linear_iteration_ratio = <integer> (25)
  growth_factor = <real>
  cutback_factor = <real>
  timestep_limiting_function = <string>
  max_function_change = <real>
  force_step_every_function_point = <bool> (false)
[../]
```

<code>dt</code>	Required. The initial timestep size.
<code>optimal_iterations</code>	The target number of nonlinear iterations for adaptive timestepping.
<code>iteration_window</code>	The size of the nonlinear iteration window for adaptive timestepping.
<code>linear_iteration_ratio</code>	The ratio of linear to nonlinear iterations to determine target linear iterations and window for adaptive timestepping.
<code>growth_factor</code>	Factor by which timestep is grown if needed.
<code>cutback_factor</code>	Factor by which timestep is cut back if needed.
<code>timestep_limiting_function</code>	Function used to control the timestep.
<code>max_function_change</code>	Maximum change in the function over a time step.
<code>force_step_every_function_point</code>	Controls whether a step is forced at every point in the function.

`IterationAdaptiveDT` grows or shrinks the time step based on the number of iterations taken to obtain a converged solution in the last converged step. The required `optimal_iterations` parameter controls the number of nonlinear iterations per time step that provides optimal solution efficiency. If more iterations than that are required to obtain a converged solution, the time step may be too large, resulting in undue solution difficulty, while if fewer iterations are required, it may be possible to take larger time steps to obtain a solution more quickly.

A second parameter, `iteration_window`, is used to control the size of the region in which the time step is held constant. As shown in Figure 19.1, if the number of nonlinear iterations for convergence is lower than $(\text{optimal_iterations} - \text{iteration_window})$, the time step is increased, while if more than $(\text{optimal_iterations} + \text{iteration_window})$, iterations are required, the time step is decreased. The `iteration_window` parameter is optional. If it is not specified, it defaults to 1/5 the value specified for `optimal_iterations`.

The decision on whether to grow or shrink the time step is based both on the number of nonlinear iterations and the number of linear iterations. The parameters mentioned above are used to control the optimal iterations and window for nonlinear iterations. The same criterion is applied to the linear iterations. Another parameter, `linear_iteration_ratio`, which defaults to 25, is used to control the optimal iterations and window for the linear iterations. These are calculated by multiplying `linear_iteration_ratio` by `optimal_iterations` and `iteration_window`, respectively.

To grow the time step, the growth criterion must be met for both the linear iterations and nonlinear iterations. If the time step shrinkage criterion is reached for either the linear or nonlinear iterations, the time step is decreased. To control the time step size only based on the number of nonlinear iterations, set `linear_iteration_ratio` to a large number.

If the time step is to be increased or decreased, that is done using the factors specified with the `growth_factor` and `cutback_factor`, respectively. If a solution fails to converge when adaptive time stepping is active, a new attempt is made using a smaller time step in the same manner as with the fixed time step methods. The maximum and minimum time steps can be optionally

specified in the `Executioner` block using the `dtmax` and `dtmin` parameters, respectively.

In addition to controlling the time step based on the iteration count, `IterationAdaptiveDT` also has an option to limit the time step based on the behavior of a time-dependent function, optionally specified by providing the function name in `timestep_limiting_function`. This is typically a function that is used to drive boundary conditions of the model. The step is cut back if the change in the function from the previous step exceeds the value specified in `max_function_change`. This allows the step size to be changed to limit the change in the boundary conditions applied to the model over a step. In addition to that limit, the boolean parameter `force_step_every_function_point` can be set to `true` to force a time step at every point in a `PiecewiseLinear` function.

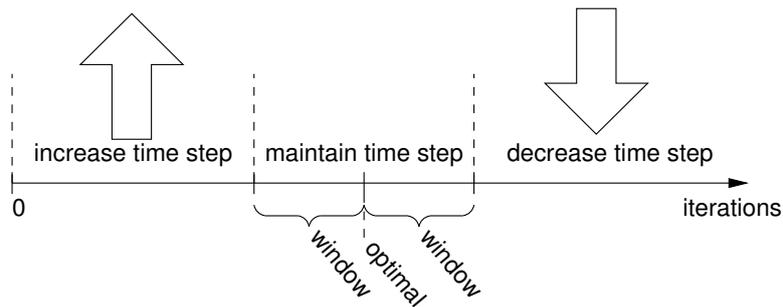


Figure 19.1: Criteria used to determine adaptive time step size

19.2 PETSc Options

The amount of PETSc options to choose as solver parameters is vast and cannot be covered in detail here. This section provides the recommended PETSc options depending upon whether Dirac or Constraint based contact is used. The values for the `petsc_options_value` can change depending on the particular problem being analyzed. For specialized problems where these standard options do not work the user is encouraged to consult the PETSc User's Manual or contact the `bison-users` mailing list.

19.2.1 Constraint Contact

The recommended PETSc options for use with Constraint based contact are given below:

```
[Executioner]
...
petsc_options_iname = '-pc_type -sub_pc_type -pc_asm_overlap
                      -ksp_gmres_restart'
petsc_options_value = 'asm lu 20 101'
...
[../]
```

19.2.2 Dirac Contact

The recommended PETSc options for use with Dirac based contact are given below:

```
[Executioner]
...
petsc_options_iname = '-ksp_gmres_restart -pc_type -pc_hypre_type
                    -pc_hypre_boomeramg_max_iter'
petsc_options_value = '201 hypre boomeramg 4'
...
[../]
```

19.3 Quadrature

When using higher order meshes (e.g. second) it is recommended to use `quadrature = true` in the thermal contact block. When this parameter is set the order of the quadrature can be specified using a `[./Quadrature]` subblock within the `[Executioner]` block as follows:

```
[./Quadrature]
type = <string>
element_order = <string>
order = <string>
side_order = <string>
[../]
```

<code>type</code>	The type of quadrature used. Default is Gauss.
<code>element_order</code>	Order of quadrature on the elements.
<code>order</code>	Order of quadrature used.
<code>side_order</code>	Order of quadrature used on the sides.

The recommended `[./Quadrature]` block when using second-order meshes is the following:

```
[./Quadrature]
order = FIFTH
side_order = SEVENTH
[../]
```

20 Outputs

The `Outputs` block lists parameters that control the frequency and type of results files produced. It is possible to create multiple output objects each outputting at different intervals, or different variables, or varying file types. The `Outputs` system is very complex and enables a large amount of customization. This section will highlight different capabilities of the system. At the end of this section an example of a typical `Outputs` block for BISON assessment cases will be presented.

20.1 Basic Input File Syntax

To enable output an input file must contain an `Outputs` block. The simplest method for enabling output is to utilize the shortcut syntax as shown below, which enables the `Console` output (prints to screen) and `Exodus` output for writing data to a file.

```
[Outputs]
  console = true    #output to the screen with default settings
  exodus = true     #output to ExodusII file with default settings
[]
```

20.2 Advanced Syntax

To take full advantage of the output system the use of subblocks is required. For example, the input file snippet below is **exactly** equivalent, including the subblock names, to the snippet shown above that utilizes the shortcut syntax.

```
[Outputs]
  [./console]
    type = Console    #output to the screen with default settings
  [../]
  [./exodus]
    type = Exodus     #output to ExodusII file with default settings
  [../]
[]
```

However, the subblock syntax allows for increased control over the output and allows for multiple outputs of the same type to be specified. For example, the following creates two `Exodus` outputs, one outputting the a mesh at every time step including the initial condition the other outputs every 3 time steps without the initial condition. Additionally, performance logging was enabled for `Console` output.

```

[Outputs]
  [./console]
    type = Console
    perf_log = true      # enable performance logging
  [../]
  [./exodus]
    type = Exodus
    output_initial = true # enable the output of the initial
                        # condition for the [ExodusII][1] file
  [../]
  [./exodus_3]
                        # create a second [Exodus II][1] output
                        # that utilizes a different output interval

    type = Exodus
    file_base = exodus_3 # set the file base
                        # (the extension is automatically applied)

    interval = 3        # only output every third step
  [../]
[]

```

20.3 Common Output Parameters

In addition to allowing for short-cut syntax, the `Outputs` block also supports common parameters. For example, `output_initial` may be specified outside of individual subblocks, indicating that all subblocks should output the initial condition. If within a subblock the parameter is given a different value, the subblock parameter takes precedence. The input file snippet below demonstrate the usage of a common values as well as the use of multiple output blocks.

```

[Outputs]
  output_initial = true      # set all subblocks to output the
                            # initial condition
  vtk = true                # output VTK file with default setting
  [./console]
    type = Console
    perf_log = true
  [../]
  [./exodus]
    type = Exodus
    output_initial = false  # this ExodusII files will not contain
                            # the initial condition
  [../]
[]

```

20.4 File Output Names

The default naming scheme for output files utilizes the input file name (e.g., input.i) with a suffix that differs depending on how the output is defined:

- outputs create using the shortcut syntax an "_out" suffix is utilized and
- subblocks use the actual subblock name as the suffix.

For example, if the input file (input.i) contained the following [Outputs] block, two files would be created: input_out.e and input_other.e.

```
[Outputs]
  console = true
  exodus = true      # creates input_out.e
  [./other]         # creates input_other.e
    type = Exodus
    interval = 2
  [../]
[]
```

20.5 Typical BISON Example

Now that some of the basic capabilities of the output system have been outlined, a typical [Outputs] block from a BISON assessment case is presented.

```
[Outputs]
  interval = 1
  output_initial = true
  csv = true
  exodus = true
  color = false
  [./console]
    type = Console
    perf_log = true
    linear_residuals = true
    max_rows = 25
  [../]
[]
```

interval	The interval at which timesteps are output to the solution file. This is a global output parameter since it is not in a subblock.
output_initial	Request that the initial condition is output to the solution file. This is a global output parameter since it is not in a subblock.
csv	Specify that a csv file be output containing values of all postprocessors.
exodus	Specify that an ExodusII file be output.

color	Specify that color not be output to the screen for the log.
type	Specify the type for the subblock. In this case Console.
perf_log	Specify that the performance log be output to the screen.
linear_residuals	Specify that the linear residuals be output to the screen.
max_rows	The maximum number of postprocessor/scalar values displayed on the screen during a timestep (set to 0 for unlimited).

21 Dampers

Dampers are used to decrease the attempted change to the solution with each nonlinear step. This can be useful in preventing the solver from changing the solution dramatically from one step to the next. This may prevent, for example, the solver from attempting to evaluate negative temperatures.

The `MaxIncrement` damper is commonly used.

21.1 MaxIncrement

The `MaxIncrement` damper limits the change of a variable from one nonlinear step to the next.

```
[Dampers]
  [./maxincrement]
    type = MaxIncrement
    max_increment = <real>
    variable = <string>
  [../]
[]
```

<code>type</code>	MaxIncrement
<code>max_increment</code>	Required. The maximum change in solution variable allowed from one nonlinear step to the next.
<code>variable</code>	Required. Variable that will not be allowed to change beyond <code>max_increment</code> from nonlinear step to nonlinear step.

22 Restart and Recover

The MOOSE framework provides two ways of continuing a simulation: recover and restart. An example restart problem is located at `projects/bison/examples/restart`. The instructions below are copied from the MOOSE Wiki.

22.1 Definitions

- **Restart:** Running a simulation that uses data from a previous simulation. Data in this context is very broad, it can mean spatial field data, non-spatial variables or postprocessors, or stateful object data. Usually the previous and new simulations use different input files.
- **Recover:** Resuming an existing simulation either due to a fault or other premature termination.
- **Solution File:** A mesh format containing field data in addition to the mesh (i.e. a normal output file).
- **Checkpoint:** A snapshot of the simulation data including all meshes, solutions, and stateful object data. Typically one checkpoint is stored in several different files.
- **N to N:** In a restart context, this means the number of processors for the previous and current simulations must match.
- **N to M:** In a restart context, different numbers of processors may be used for the previous and current simulations.

22.2 Simple Restart (Variable initialization)

- This method is best suited for restarting a simulation when the mesh in the previous simulation exactly matches the mesh in the current simulation and only initial conditions need to be set for one more variables.
- This method requires only a valid Solution File.
- MOOSE supports N to M restart when using this method.

```

# Reading field data from a nodal or elemental field from a
# previous simulation
[Mesh]
  # MOOSE supports reading field data from ExodusII, XDA/XDR, and
  # mesh checkpoint files (.e, .xda, .xdr, .cp)
  file = previous.e
  # This method of restart is only supported on serial meshes
  distribution = serial
[]

[Variables]
  [./nodal]
    family = LAGRANGE
    order = FIRST
    initial_from_file_var = nodal
    initial_from_file_timestep = 10
  [../]
[]

[AuxVariables]
  [./elemental]
    family = MONOMIAL
    order = CONSTANT
    initial_from_file_var = elemental
    initial_from_file_timestep = 10
  [../]
[]

```

22.3 Enabling Checkpoints

Advanced restart in MOOSE requires checkpoint files. To enable automatic checkpoints using the default options (every time step, and keep last two) in your simulation simply add the following flag to your input file:

```

[Outputs]
  checkpoint = true
[]

```

If you need more control over the checkpoint system, you can create a subblock in the input file that will allow you to change the file format, suffix, frequency of output, the number of checkpoint files to keep, etc. For a complete list see the Doxygen page for Checkpoint.

Note: You should always set `num_files` to at least 2 to minimize the change of ending up with a corrupt restart file.

```

[Outputs]
  [./my_checkpoint]
    type = Checkpoint

```

```
    num_files = 4
    interval = 5
  [../]
[]
```

22.4 Advanced Restart

- This method is best suited for situations when the mesh from the previous simulation and the current simulation match but all variables should be reloaded and all stateful data should be restored.
- Support for modifying some variables is supported such as `dt` and `time_step`. By default, MOOSE will automatically use the last values found in the checkpoint files.
- Only N to N restarts are supported using this method.

```
[Mesh]
# Serial number should match corresponding Executioner parameter
file = out_cp/0010_mesh.cpr
# This method of restart is only supported on serial meshes
distribution = serial
[]

[Executioner]
type = Transient

# Note that the suffix is left off in the parameter below.
restart_file_base = out_cp/0010
[]
```

22.5 Reloading Data

It is possible to load and project data onto a different mesh from a solution file usually as an initial condition in a new simulation. MOOSE fully supports this through the use of `SolutionUserObject` (see Section 23.3).

22.6 Recover

Whenever MOOSE is being run with checkpoints enabled, a simulation that has terminated due to a fault can be recovered simply by using the `--recover` CLI flag.

As a supplement to this example, also included is a `restart.sh` script (`bison/examples/restart`), which can serve as an example and reference for commands to use when using `restart`. The purpose of this script is to test the functionality of `restart`.

23 UserObjects

23.1 FuelPinGeometry

FuelPinGeometry computes the fuel rod outer dimensions, the height, ID, and OD of the fuel stack, and the pellet-clad gap directly from the mesh so that it can be used by other objects such as Burnup, RelocationUO2, and HydrogenPickup.

```
[./pin_geometry]
type = FuelPinGeometry
clad_inner_wall = <string>( "5" )
clad_outer_wall = <string>( "2" )
clad_top = <string>( "3" )
clad_bottom = <string>( "1" )
pellet_exteriors = <string>( "8" )
[../]
```

type	FuelPinGeometry
clad_inner_wall	Sideset for inner wall of cladding, not including end caps.
clad_outer_wall	Sideset for outer wall of cladding.
clad_top	Sideset for top of cladding (top of upper end cap).
clad_bottom	Sideset for bottom of cladding (bottom of lower end cap).
pellet_exteriors	Sideset for all pellet exteriors.

23.2 PelletBrittleZone

PelletBrittleZone computes the brittle zone width on a per-pellet basis.

```
[./pelletbrittlezone]
type = PelletBrittleZone
pellet_id = <string>
temp = <string>
pellet_radius = <real>
a_lower = <real>
a_upper = <real>
number_pellets = <integer>
fuel_pin_geometry = <string>
[../]
```

type	PelletBrittleZone
pellet_id	Variable name for pellet id. Typically pellet_id.
temp	Name of temperature variable. Typically temp.
pellet_radius	Required if fuel_pin_geometry is not specified. The outer radius of the fuel.
a_lower	Required if fuel_pin_geometry is not specified. The lower axial coordinate of the fuel stack.
a_upper	Required if fuel_pin_geometry is not specified. The upper axial coordinate of the fuel stack.
number_pellets	Required. Number of fuel pellets.
fuel_pin_geometry	Name of the FuelPinGeometry object (see 23.1).

23.3 SolutionUserObject

A solution user object reads a variable from a mesh in one simulation to another. In order to use a SolutionUserObject three additional parameters are required, an AuxVariable, a Function and an AuxKernel. The AuxVariable represents the variable to be read by the solution user object. The SolutionUserObject is set up to read the old output file. A SolutionFunction is required to interpolate in time and space the data from the SolutionUserObject. Finally, the FunctionAux is required that will query the function and write the value into the AuxVariable. An example of what additions are required to the input file is shown below:

```
[AuxVariables]
  [./temp]
  [../]
[]

[Functions]
  [./interpolated_temp]
    type = SolutionFunction
    from_variable = 'temp'
    solution = read_thermo_solution
  [../]
[]

[UserObjects]
  [./read_thermo_solution]
    type = SolutionUserObject
    mesh = 'temp_from_another_simulation.e'
    execute_on = 'residual'
    nodal_variables = 'temp'
  [../]
[]

[AuxKernels]
```

```
[./interp_temp]
  type = FunctionAux
  variable = 'temp'
  function = 'interpolated_temp'
[../]
[]
```

Note that in the `SolutionUserObject` subblock that the `mesh` parameter is **required**.

24 Reference Residual Problem

An advanced scenario that requires the addition of a [Problem] block in the input file is the ReferenceResidualProblem. Reference residual is an alternative way to signify convergence of a timestep. The structure of the [Problem] block for a two-dimensional axisymmetric simulation is as follows:

```
[./referenceresidualproblem]
  coord_type = RZ
  type = ReferenceResidualProblem
  solution_variables = <string list>
  reference_residual_variables = <string list>
  acceptable_iterations = <integer> (0)
  acceptable_multiplier = <integer> (1)
[../]
```

type	ReferenceResidualProblem
solution_variables	Set of variables to be checked for relative convergences.
reference_residual_variables	Set of variables that provide reference residuals for the relative convergence check.
acceptable_iterations	Iterations after which convergence to acceptable limits are accepted.
acceptable_multiplier	Multiplier applied to relative tolerance for acceptable limit.

When using reference residual it is typically acceptable to loosen the relative tolerance for convergence by an order of magnitude. The difficulty in setting up a ReferenceResidualProblem currently is the requirement of creating an AuxVariable for each of the reference residual variables. Then for each Kernel that the corresponding solution variable applies to an additional line is required to save into the reference residual variable. This requires significant changes to the input file. If you would like to try using a ReferenceResidualProblem, please contact one of the BISON developers for more detailed instructions of setting it up.

The implementation of ReferenceResidualProblem is scheduled to be updated within the next year.

25 Frictional Contact Problem

Another advanced use of the [Problem] block is the FrictionalContactProblem. This is used when a user wants to use kinematic (default) enforcement of frictional contact. If a user wants to use the penalty method for frictional contact the `friction_coefficient` needs to be specified in the [Contact] block and the `model` parameter set to `coulomb`. A typical [Problem] block for a two-dimensional axisymmetric case is as follows:

```
[./frictionalcontactproblem]
  coord_type = RZ
  type = FrictionalContactProblem
  friction_coefficient = <real>
  master = <string list>
  slave = <string list>
  slip_factor = <real>
  slip_too_far_factor = <real>
  disp_x = <string>
  disp_y = <string>
  residual_x = <string>
  residual_y = <string>
  diag_stiff_x = <string>
  diag_stiff_y = <string>
  inc_slip_x = <string>
  inc_slip_y = <string>
  contact_slip_tolerance_factor = <real> (10)
  target_contact_residual = <real>
  maximum_slip_iterations = <integer> (100)
  minimum_slip_iterations = <integer> (1)
  slip_updates_per_iteration = <integer> (1)
  solution_variables = <string list>
  reference_residual_variables = <string list>
[../]
```

<code>type</code>	FrictionalContactProblem
<code>friction_coefficient</code>	Required. The friction coefficient applied between the interacting surfaces.
<code>master</code>	Required. Number or name IDs of the master surfaces for which slip should be calculated.
<code>slave</code>	Required. Number or name IDs of the slave surfaces for which slip should be calculated.

<code>slip_factor</code>	Required. The fraction of calculated slip to be applied for each interaction. A value of 1 means the entire amount of calculated slip is applied.
<code>slip_too_far_factor</code>	Required. The fraction of the calculated slip to be applied for each interaction that is in the slipped-too-far-state.
<code>disp_x</code>	Required. Variable name for the x-displacement. Typically <code>disp_x</code> .
<code>disp_y</code>	Required. Variable name for the y-displacement. Typically <code>disp_y</code> .
<code>residual_x</code>	Required. Name of auxiliary variable containing the saved x residual.
<code>residual_y</code>	Required. Name of auxiliary variable containing the saved y residual.
<code>diag_stiff_x</code>	Required. Name of auxiliary variable containing the saved x diagonal stiffness.
<code>diag_stiff_y</code>	Required. Name of auxiliary variable containing the saved y diagonal stiffness.
<code>inc_slip_x</code>	Required. Name of auxiliary variable used to store the incremental slip in the x direction.
<code>inc_slip_y</code>	Required. Name of auxiliary variable used to store the incremental slip in the y direction.
<code>contact_slip_tolerance_factor</code>	Multiplier on convergence criteria to determine when to start slipping.
<code>target_contact_residual</code>	Frictional contact residual convergence criterion.
<code>target_relative_contact_residual</code>	Frictional contact relative residual convergence criterion.
<code>maximum_slip_iterations</code>	Maximum number of slip iterations per step.
<code>minimum_slip_iterations</code>	Minimum number of slip iterations per step.
<code>slip_updates_per_iteration</code>	The number of slip updates per contact iteration.
<code>solution_variables</code>	Set of variables to be checked for relative convergences.
<code>reference_residual_variables</code>	Set of variables that provide reference residuals for the relative convergence check.

It can be seen that a significant amount of auxiliary variables are required to be added to the input file to make `FrictionalContactProblem` work. In addition references to saved variables as in the `ReferenceResidualProblem` case is also required. If you would like to use `FrictionalContactProblem` please contact a BISON developer for assistance. The implementation and robustness of `FrictionalContactProblem` is to be improved in the next year.

26 Mesh Script

26.1 Overview

To ease generation of LWR fuel meshes, a mesh script is available. The script relies on CUBIT [6].

26.1.1 Run the Main Script

The mesh script is at `bison/tools/U02/`. The main script (`mesh_script.sh`) is run from the shell command line. This script invokes the Python meshing script (`mesh_script.py`) and passes it an input file named `mesh_script_input.py` by default.

You invoke the script as:

```
> ./mesh_script.sh [-c -d -l] [-p path to mesh_script.py] [-i  
  mesh_script_input.py] [-o output file name]
```

The `-c` flag will cause the script to check whether CUBIT can be loaded. The `-d` flag results in the deletion of the CUBIT journal file when the script completes. The `-l` flag will generate a log file (otherwise messages will go to the terminal). The `-p` flag, which is rarely used, tells the script where to find the `mesh_script.py` file. You may supply any mesh script input file with the `-i` flag. Finally, you may specify the name of the output Exodus file with the `-o` flag.

The main script generates an exodus file, with QUAD elements in 2D and HEX elements in 3D.

26.1.2 Mesh Architecture

Figure 26.1 provides an overview of the architecture of a fuel rod. A fuel rod is composed of a clad, a stack of pellets, and optionally a liner extruded on the inner surface of the clad. Each component of this architecture corresponds to a different block in the BISON input and mesh files. In the mesh input file, you refer to each block through a specific dictionary to create it. In the Exodus file, blocks are numbered, and a name is provided for each of them.

The pellets contained in a fuel rod can have different geometries. There is a block for each geometry, in the input file as well as in the Exodus file.

26.2 Input File Review

26.2.1 Pellet Type

This dictionary encapsulates a pellet geometry and the quantity of the corresponding pellets. To refer to a parameter, you have to know its key (the quoted string between brackets).

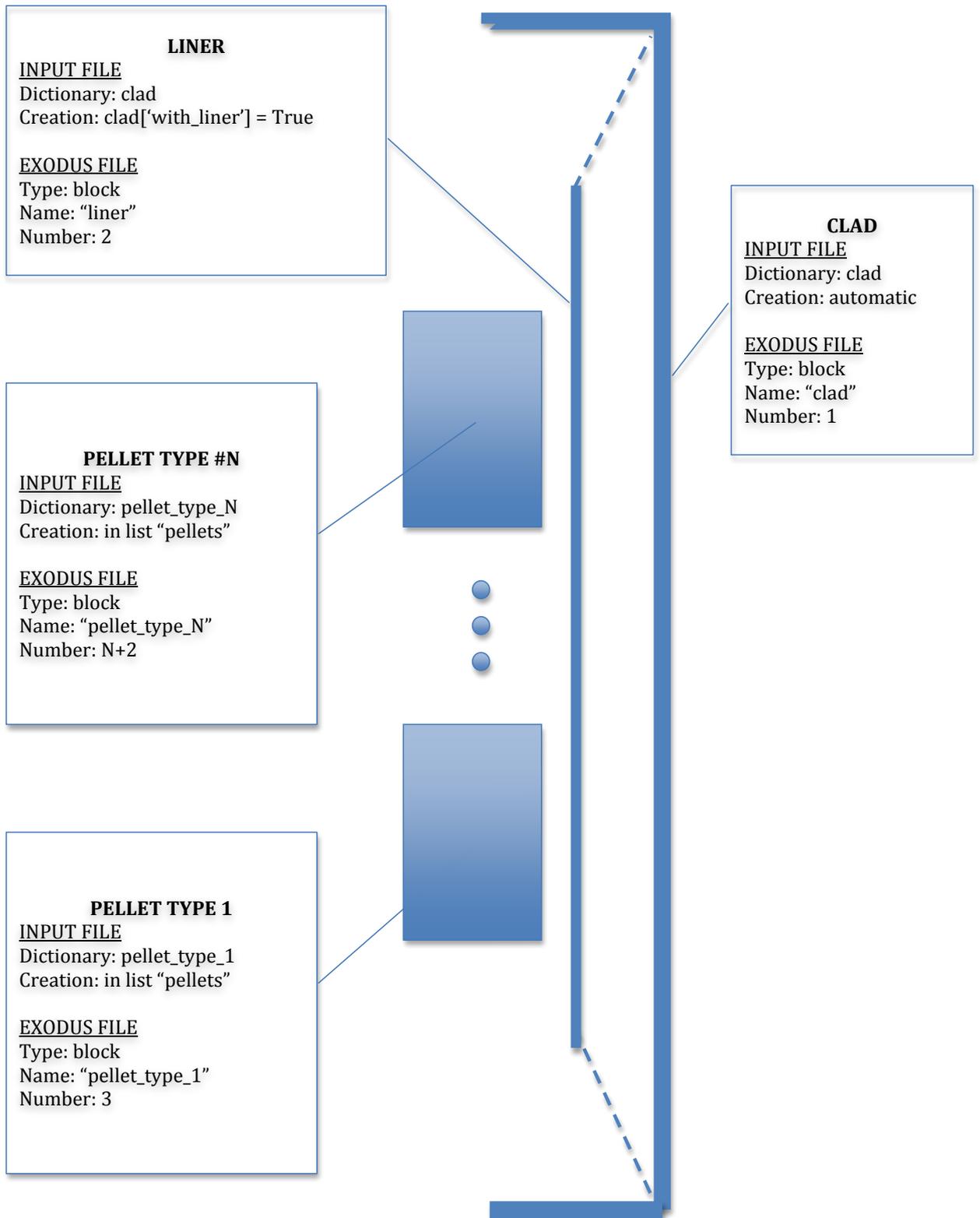


Figure 26.1: Overview of the architecture of a fuel rod.

```

# Pellet Type 1
Pellet1= {}
Pellet1['type'] = 'discrete'
Pellet1['quantity'] = 5
Pellet1['mesh_density'] = 'medium'
Pellet1['outer_radius'] = 0.0041
Pellet1['inner_radius'] = 0
Pellet1['height'] = 2*5.93e-3
Pellet1['dish_spherical_radius'] = 1.01542e-2
Pellet1['dish_depth'] = 3e-4
Pellet1['chamfer_width'] = 5.0e-4
Pellet1['chamfer_height'] = 1.6e-4

```

- 'type' Type *string*. Must be 'discrete' or 'smeared'. From a geometric point of view, a smeared pellet is a rectangle. Two consecutive smeared pellets have their top and bottom surfaces merged.
- 'quantity' Type *int*. Number of pellets created with this geometry.
- 'mesh_density' Type *string*.
- 'outer_radius' Type *float*. Outer radius of the pellet.
- 'inner_radius' Type *float*. Inner radius of the pellet.
- 'height' Type *float*. Pellet height.
- 'dish_spherical_radius' Type *float*. Spherical radius of the dishing. Needed only if type is 'discrete'.
- 'dish_depth' Type *float*. Depth of the dishing. Needed only if type is 'discrete'.
- 'chamfer_width' Type *float*. Radial chamfer length in RZ coordinates. Must be zero for a non-chamfered pellet. Needed only if type is 'discrete'.
- 'chamfer_height' Type *float*. Axial chamfer length in RZ coordinates. Must be zero for a non-chamfered pellet. Needed only if type is 'discrete'. If either `chamfer_width` or `chamfer_height` is zero, both must be zero.

26.2.2 Pellet Collection

```
pellets = [Pellet1, Pellet2, Pellet3]
```

This is a list of the pellets that make up the pellet stack. The geometries are ordered from the bottom to the top of the stack. A pellet type block must be present in this list to be created.

26.2.3 Stack Options

```
# Stack options
pellet_stack = {}
pellet_stack['merge_pellets'] = True
pellet_stack['higher_order'] = False
pellet_stack['angle'] = 0
```

- 'merge_pellets' Type *string*. Control type of merging between pellets. Options are: 'yes', 'no', 'point', 'surface'. See Table 26.1 for a complete description. **Note that any other string results in pellets that are not merged.**
- 'higher_order' Type *boolean*. Control order of mesh elements. See Table 26.2
- 'angle' Type *int*. Between 0 and 360. Angle of revolution of the pellet stack. If 0, creates a 2D fuel rod. If greater than 0, creates a 3D fuel rod.

	2D discrete	2D smeared	3D discrete
'yes'	vertex	curve	curve
'no'	not merged	not merged	not merged
'point'	vertex	vertex	curve
'surface'	not merged	curve	not merged

Table 26.1: Merging control. 'Vertex' means that the pellets are merged at their common vertex which is the closest from the centerline. In 2D, 'curve' means that the pellets are merged at their common curve. In 3D, 'curve' means that the pellets are merged at the curve generated by the corresponding merged vertex in 2D RZ geometry.

	False	True
2D	QUAD4	QUAD8
3D	HEX8	HEX20

Table 26.2: Order of generated elements

26.2.4 Clad

```
clad = {}
clad['mesh_density'] = 'medium'
clad['gap_width'] = 8e-5
clad['bot_gap_height'] = 1e-3
clad['top_gap_height'] = 1.67e-3
clad['clad_thickness'] = 5.6e-4
```

```

clad['top_bot_clad_height'] = 2.24e-3
clad['plenum_fuel_ratio'] = 0.045
clad['with_liner'] = False
clad['liner_width'] = 5e-5

```

- 'mesh_density' Type *string*. CAUTION: the mesh density of the clad is related to the mesh density of the pellets which use the *same* mesh dictionary as the clad.
- 'gap_width' Type *float*. Radial width of the gap between the fuel and the clad (or the liner).
- 'bot_gap_height' Type *float*. Axial gap height between bottom of fuel and the cladding.
- 'top_gap_height' Type *float*. Axial gap height between top of fuel and the cladding. Either this or 'plenum_fuel_ratio' must be given.
- 'clad_thickness' Type *float*. Thickness of the sleeve of the clad.
- 'top_bot_clad_height' Type *float*. Height of the bottom and of the top of the clad.
- 'plenum_fuel_ratio' Type *float*. Ratio of the axial gas height to the fuel height inside the cladding. Either this or 'top_gap_height' must be given.
- 'with_liner' Type *boolean*. Whether to include a liner.
- 'liner_width' Type *float*. Liner width.

26.2.5 Meshing Parameters

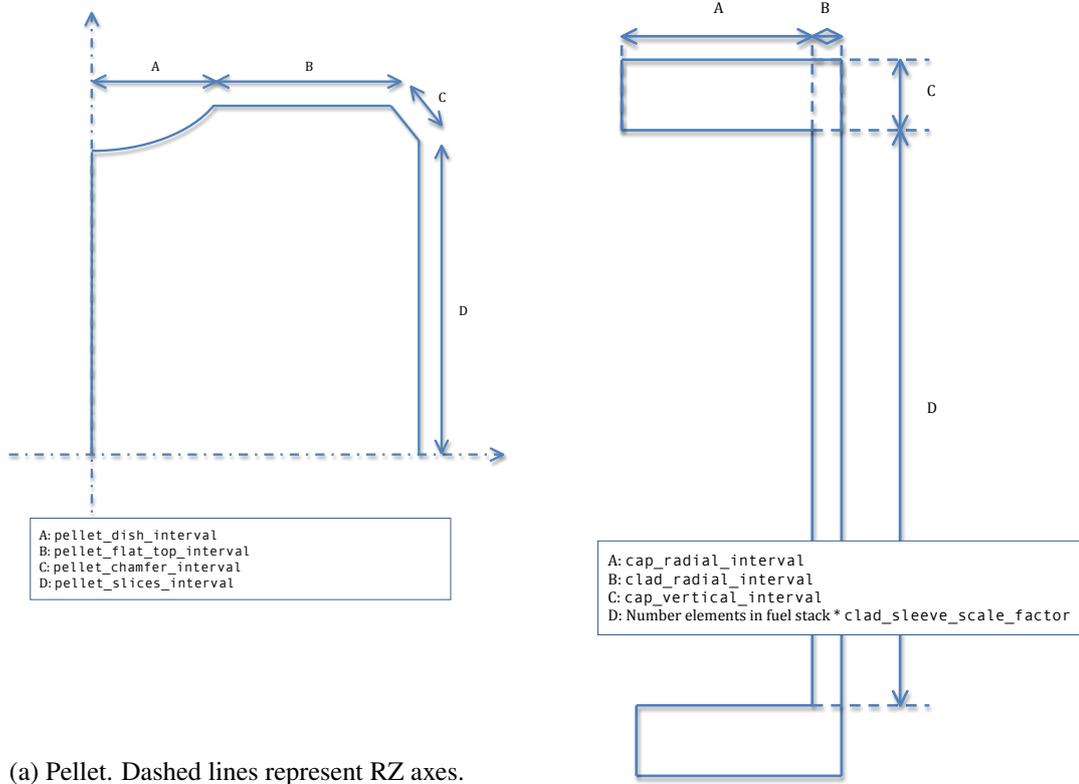
```

# Parameters of mesh density 'coarse'
coarse = {}
coarse['pellet_r_interval'] = 6
coarse['pellet_z_interval'] = 2
coarse['pellet_dish_interval'] = 3
coarse['pellet_flat_top_interval'] = 2
coarse['pellet_chamfer_interval'] = 1
coarse['pellet_slices_interval'] = 4
coarse['clad_radial_interval'] = 3
coarse['clad_sleeve_scale_factor'] = 4
coarse['cap_radial_interval'] = 6
coarse['cap_vertical_interval'] = 3
coarse['pellet_angular_interval'] = 6
coarse['clad_angular_interval'] = 12

```

The user defines a dictionary containing the mesh parameters. The user can specify the name of this dictionary as long as the name is consistent with the names defined in the pellet type

Figure 26.2: Mesh parameters



(a) Pellet. Dashed lines represent RZ axes.

(b) Clad. Represented in RZ.

blocks for mesh_density. pellet_r_interval and pellet_z_interval are used only with smeared pellet meshes. Figure 26.2 explains other parameters.

The angular intervals are for 3D geometries and correspond to the created arcs of circle. Note that to have a nice mesh, you may want to have the same number of interval on the diameter of the fuel rod and on this arc of circle.

26.3 Output File Review

Figure 26.1 summarizes names and number of the blocks in the exodus file. Figure 26.4 summarizes the numbering for the sidesets and nodesets.

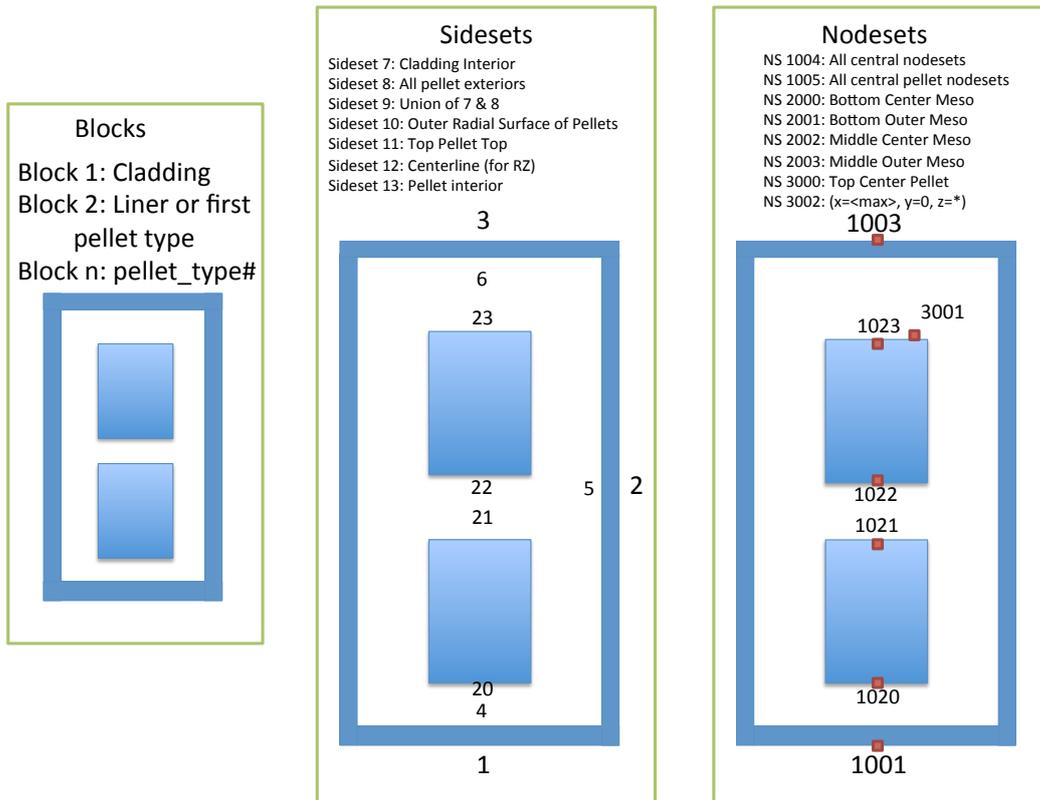


Figure 26.4: Sidesets, nodesets and blocks ids in the exodus file

26.4 Things to Know

26.4.1 Main Script

The main script is written in python v2.5. It is organized in classes: Pellet, PelletStack, Clad, Liner and FuelRod. The link between the input file and the main is assured by three functions.

A first function is charged to pick read the input file. A second function checks that the syntax of the input file makes sense for the main script. The third function creates the mesh based on the input file.

26.4.2 Error Messages

AttributeError Caused by a missing class in the input file.

KeyError Often is caused by a wrong key in the input file. The main script should check that the keys entered in the input file are valid and specify which key is not valid if it occurs.

Other errors should be accompanied by a descriptive message. Contact the developers if the error message is not helpful.

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